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Preface

This thesis is submitted as a partial fulfilment of the requirements for the Danish PhD degree and is the result of three years' research carried out at the Civil Engineering Department at the Technical University of Denmark.

I would like to thank my supervisor, Professor Svend Svendsen, for giving me the opportunity to become a PhD student and for his guidance and encouragement during the course of my PhD study. I would also like to thank all my colleagues in the Section of Building Physics and Services. Special thanks go to my office mate and friend, Marek Brand, for his continuous support and tolerance of my constant interruptions, and to Diana Lauritsen for many helpful discussions over a cup of tea or during our many rides home.

My gratitude is also extended to the Interreg IVa programme and the Transport and Energy Ministry's Energy Research Programme (EFP) for partial funding of my PhD project. I would also like to extend my thanks to all the project partners for accepting me as a full-value team member.

Thanks also go to my colleagues at the NRCan - CanmetENERGY for some inspiring months during my external stay in spring-summer of 2012. I would especially like to thank Meli Stylianou for accepting me as part of the research group and José Candanedo for fruitful discussions and making me feel at home in Montreal.

Many thanks also to my family and friends in Belgium for being there for me during my visits, but also for supporting me 1000 km from home. Finally, a very special note of thanks is extended to my boyfriend, Morten, for his invaluable support, patience and not least the nice home-cooked meals during the final stages of my PhD study.

Lyngby, 19th November 2013

Lies Vanhoutteghem

Abstract

There is a need to reduce energy consumption in buildings and in general improve energy efficiency in the building sector in Denmark, as in the rest of the EU. Energy savings, however, should go hand in hand with providing a healthy and comfortable indoor environment. So, the aim of this thesis is to contribute to the development of Danish low-energy residential buildings with good indoor environment. To reach the target of a fossil-free energy supply in Denmark by 2050, both new building design and renovation of existing buildings to meet future energy requirements need to be taken into account.

To encourage the development of appropriate designs for new low-energy buildings and façade renovation of existing buildings, improved knowledge is needed on window design. The research consisted of two parts. First in relation to window design in a typical Danish single-family house constructed in accordance with current and future energy requirements, the influence of window size, type and orientation on space heating demand and thermal indoor environment were investigated in EnergyPlus by comparing a window design with an even distribution (same glazing-to-floor-area in each room) with a traditional window design with large south-oriented windows. The influence of the thermal zone configuration on the prediction of space heating demand and thermal indoor environment, and therefore on the choice of window design, was also investigated. When distinguishing between thermal zones with direct and non-direct solar gains, results showed that the choice of window size and orientation is no longer a big issue from the perspective of heating demand as long as low glazing U-values are used. If an even window distribution is used in combination with an appropriate venting rate and solar control in critical south-oriented rooms, windows can be positioned in the façade of well-insulated residential buildings with considerable architectural freedom. Second, daylight was considered and the relationship between various window parameters (glazing area, orientation, U-value, g-value and light transmittance) and how these affect energy performance, daylight and thermal indoor environment was investigated using DAYSIM and EnergyPlus for rooms with various geometries. With regard to daylight performance, a climate-dependent daylight factor taking into account building location was used and compared with the use of climate-based modelling. Charts illustrating a space of solutions for space heating demand defined by targets for daylight and thermal indoor environment were used to discuss the effect of different window parameters and potential conflicts related to window design were identified in deep or narrow south-oriented side-lit rooms in well-insulated dwellings. Thereafter, recommendations on window solutions were given based on results showing that they can be chosen on a room-by-room basis with the choice of glazing-to-floor ratio based on daylight requirements. To achieve a good thermal indoor environment and minimum space heating demand, for example, a high g-value is recommended in north-oriented rooms, and glazing with solar-control coating can be used as an alternative to dynamically controlled solar shading in south-oriented rooms.

While these recommendations were given as a starting point for selecting a good window design in the early design phases, energy performance and thermal indoor environment are also determined by a building's energy system and need to be considered for each specific building. Architects, engineers and builders often do not possess the necessary simplified tools for the early stages of the design process where the most important decisions are made. This research therefore introduces a simplified tool, called WinDesign, which can be used in the early design phases for selection of window design, but also more generally for the prediction of building performance. The development and validation of the tool, which uses a 4-step method, showed how windows can be selected with regard to energy use, thermal indoor environment, cost, and to a certain extent daylight (based on electricity consumption for artificial lighting). Because the tool is based on simple methods as described in EN ISO 13790 and requires limited input data, analysis can be performed relatively fast compared to more advanced tools. One of the limitations of the tool is that it does not include daylight analysis. Other user-friendly and simple tools should then be used. An example of such use is given in this thesis.

To renovate existing single-family houses to low-energy standards and to speed up this renovation, an integrated approach based on the application of the full-range of technical renovation solutions is needed. Homeowners need help with the design and decision-making, so this thesis introduces a method for renovation based on an ideal one-stop shopping concept. Through contact with a single actor, the house owner is provided with a full-service package, including all the steps necessary for the renovation: consulting, quotation for the work, financing, management of the contract work, and follow-up. Using such a full-service package can improve the quality and efficiency of a renovation, which can reduce the investment costs and make the whole renovation process easier and more attractive for building owners. However, for successful implementation of the method, more research is needed into marketing strategies and incentive structures. As part of the method, renovation packages targeted at various types of single-family houses are also suggested. The main focus, however, is on the segment of single-family houses built in the period between 1960 and 1980, and houses built before 1930. The results show that both types of single-family houses could be renovated to a level of energy performance which is comparable to the requirements for new houses today, but only if extensive post-insulation is combined with energy-efficient building systems. If future energy requirements are to be met, however, further research in other energy-saving measures and new materials will be needed.

Resumé

Der er behov for at reducere energiforbruget i bygninger, samt generelt at forbedre energieffektiviteten i byggesektoren i Danmark, som i resten af EU. Energibesparelser bør dog gå hånd i hånd med at sikre et sundt og behageligt indeklima. Formålet med denne afhandling er at bidrage til udviklingen af danske lavenergihuse med et godt indeklima. For at nå målet med en fossilfri energiforsyning i Danmark i 2050, skal der tages hensyn til både nybyggeri og renovering af eksisterende bygninger for at imødekomme fremtidens energibehov.

For at tilskynde udviklingen af passende design af nye lavenergibygninger og facaderenovering af eksisterende bygninger, er der behov for mere viden om vinduesdesign. I forhold til vinduesdesignet i et typisk dansk enfamiliehus konstrueret i overensstemmelse med de nuværende og fremtidige energikrav, blev indflydelsen af vinduesstørrelse, -type og orientering af vinduerne undersøgt i forhold til rumvarmebehov og termisk indeklima i EnergyPlus ved at sammenligne et vinduesdesign med en jævn fordeling (samme rude-til-gulv-areal i hvert værelse), med et traditionelt vinduesdesign med store sydvendte vinduer. Betydningen af at inddele bygningen i termiske zoner på resultatet af rumvarmebehov og termisk indeklima, og dermed valget af vinduesdesign, blev også undersøgt. Når der skelnes mellem termiske zoner med direkte og indirekte solinskud, viste resultaterne, at valget af vinduets størrelse og retning ikke længere udgører en stor del af varmebehovet, så længe en lav U-værdi anvendes. Hvis en jævn vinduesfordeling anvendes i kombination med en passende udluftning og solafskærmning i de kritiske sydvendte rum, kan vinduerne i velisolerede bygninger placeres med stor arkitektonisk frihed. Derudover blev dagslyset undersøgt. Forholdet mellem forskellige vinduesparametre (rudeareal, orientering, U-værdi, g-værdi og lystransmittans) og hvordan disse påvirker energiforbruget, dagslys og termisk indeklima blev ved hjælp af DAYSIM og EnergyPlus undersøgt i rum med forskellige geometrier. Med hensyn til dagslys blev en klimaafhængige dagslysfaktor, der tager hensyn til bygnings placering anvendt og sammenlignet ved brug af en klimabaseret dagslys modellering. Diagrammer, som illustrerer et rum af løsninger for rumvarmebehov defineret af mål for dagslys og termisk indeklima blev brugt til at diskutere effekten af forskellige vinduesparametre. Potentielle konflikter i relation til vinduesdesign blev heraf identificeret til at være i dybe eller smalle sydvendte værelser i velisolerede boliger. Derefter blev der givet anbefalinger om vinduesløsninger baseret på resultater, der viser, at de kan vælges på værelsesbasis, mens valg af rude-til-gulv-forholdet er baseret på krav til dagslys. For at opnå et godt termisk indeklima og minimalt rumvarmebehov, er en høj g-værdi anbefalet i nordvendte værelser, mens ruder med solafskærmende belægning kan bruges som et alternativ til dynamisk styret solafskærmning i sydvendte værelser.

Mens disse anbefalinger blev givet som et udgangspunkt for at vælge et godt vinduesdesign i de tidlige designfaser, er energimæssige ydeevne og termisk indeklima også bestemt af en bygnings energisystem og bør overvejes for hver enkelt bygning. Arkitekter, ingeniører og bygherrer er ofte ikke i besiddelse af de nødvendige forenklede værktøjer til de tidlige faser af designprocessen, hvor de vigtigste beslutninger bliver truffet. Denne forskning indfører derfor et forenklet værktøj, kaldet WinDesign, som kan anvendes i de tidlige projekteringsfaser for valg af vinduesdesign, men også mere generelt til forudsigelse af opbygningens ydeevne. Udvikling og validering af værktøjet, som bruger en 4 - trins metode, viste, hvordan vinduerne kan vælges med hensyn til energiforbrug, termisk indeklima, omkostninger og til en vis grad dagslys (baseret på elforbrug til kunstig belysning). Fordi værktøjet er baseret på simple metoder som beskrevet i EN ISO 13790 og kræver begrænsede input-data, kan analysen udføres relativt hurtigt i forhold til mere avancerede værktøjer. En af begrænsningerne for værktøjet er, at det ikke omfatter dagslysanalyse. Andre brugervenlige og enkle værktøjer skal bruges til dette. Et eksempel på en sådan anvendelse er givet i denne afhandling.

For at renovere de eksisterende enfamiliehuse til lavenergi-standarder og for at fremskynde denne renovering, er der behov for en integreret tilgang baseret på anvendelsen af den fulde vifte af tekniske renoveringsløsninger. Boligejere har brug for hjælp med design og beslutningstagning, så denne afhandling introducerer en metode til renovering baseret på et ideelt one-stop-shop koncept. Gennem kontakt med en enkelt aktør, er husets ejer forsynet med en fuld servicepakke, der inkluderer alle de nødvendige skridt til renoveringen: rådgivning, tilbud på arbejdet, finansiering, forvaltning af entreprisen og opfølgning. Ved hjælp af sådan en fuld servicepakke kan kvaliteten og effektiviteten af en renovering forbedres, hvilket kan reducere investeringsomkostningerne og gøre hele renoveringsprocessen lettere og mere attraktivt for bygherrer. Men for en vellykket gennemførelse af den metode, er der behov for mere forskning i strategier for markedsføring og former for tilskyndelse. Som en del af metoden, er renoveringspakker rettet mod forskellige typer af enfamiliehuse også foreslået. Hovedfokus er på segmentet af enfamiliehuse der er bygget i perioden mellem 1960 og 1980, og huse bygget før 1930. Resultaterne viser, at begge typer af enfamiliehuse kunne blive renoveret til et niveau af energiforbrug, der er sammenlignelig med kravene til nye huse i dag, men kun hvis en omfattende efterisolering er kombineret med energieffektive installationer. Hvis fremtidens energikrav skal opfyldes, vil der dog være behov for yderligere forskning i andre energibesparende foranstaltninger og nye materialer.

Abbreviations

BIM	Building Information Model
CBDM	Climate-Based Daylight Modelling
CCE	Cost of Conserved Energy [monetary unit/kWh]
DA	Daylight Autonomy [%]
DF	Daylight Factor [%]
DRY	Design Reference Year
EPBD	Energy Performance of Buildings Directive
IDM	Information Delivery Manual
IDP	Integrated Design Process
IFC	Industry Foundation Classes
IWEC	International Weather for Energy Calculations
nZEB	‘nearly zero-energy’ buildings
NEG	Net Energy Gain [kWh/m^2]
NPV	Net Present Value [monetary unit]
PMV	Predicted Mean Vote [-]
PPD	Percentage People Dissatisfied [%]
VHR	Ventilation with Heat Recovery
WERS	Window Energy Rating System

Nomenclature

I	Solar radiation during heating season, corrected for the dependency of the total solar energy transmittance on the incidence angle [kWh/m^2]
g_w	Total solar energy transmission of the window
D	Number of degree hours during heating season [kKh]
U_w	Thermal transmittance of window at incidence angle of 0° [W/m^{2}K]
$F_{sh,with}$	Utilisation factor for movable solar shading
$E_{windows}$	Energy consumption of windows [kWh/m2]
A_w	Window area [m^2]
G	Number of degree hours calculated for a reference indoor temperature of 20ºC [kKh]
η_{gn}	Dimensionless utilisation factor for solar gains
η_{ls}	Dimensionless utilisation factor for heat losses
A_{sol}	Effective collecting window area for a given orientation and tilt angle
I_{sol}	Total incident solar radiation per square metre of window area for a given orientation and tilt angle [kWh/m^2]
A_{floor}	Heated floor area of the dwelling [m^2]
$I_{setpoint}$	Illuminance at set point [lx]
$DF_{setpoint}$	Daylight factor at set point [%]
$I_{ext,hor}$	Illuminance on exterior horizontal plane without corrections for shade from exterior objects taken into account
P	Amount of power supplied by artificial lighting system [W]
$I_{thresholdvalue}$	Threshold value for activation of artificial lighting system [lx]
$I - I_{ref}$	Investment cost [monetary unit]
$E_{ref} - E$	Annual savings [kWh]
d	Net discount rate
n	Economic evaluation period [years]

Index

CS	Cooling season
HS	Heating season
i	Specific window i
max	Maximum
min	Minimum

Table of content

1 Introduction

The last couple of years have seen increasing focus on improving energy efficiency and reducing energy consumption in the building sector and this is reflected in both national and international strategies and policies (DEA, 2013, EU, 2010). In Denmark and the rest of the European Union, building energy consumption represents between 30 and 40 per cent of the total energy consumption (EC, 2010), which makes it a target for potential cost-effective energy savings. As part of European energy strategy and policy for improving energy efficiency in the building sector and reducing the use of fossil fuels, all new buildings are to be designed and constructed as ‘nearly-zero-energy’ buildings (nZEB) in 2020 (EU, 2010). This creates a strong need for research in cost-effective technology and solutions that will help meet these ambitious energy reductions without compromising on essential human needs for a healthy, comfortable indoor environment.

It is well-known that windows have considerable influence on both energy consumption and indoor environment and are among the most crucial and complex elements in the building envelope. In office buildings, most of the energy is used for cooling and lighting, whereas most of the energy used in low-energy residential buildings is for heating. This means that passive solar heating is often considered a central issue because making use of solar heat gains through properly oriented energy-efficient windows is a free way of reducing heating demand. However, recent demonstration projects (Larsen and Jensen, 2009, Larsen, 2011, Brunsgaard et al., 2012) have shown that overheating problems occur in low-energy residential buildings designed on the basis of extensive use of passive solar heat gains on south-oriented façades if no solar control measures are used. If window design is properly selected, low-energy buildings should make efficient use of solar heat gains to reduce heating demand and at the same time avoid too much heat gain which could result in overheating. The design of low-energy buildings needs to take into account both winter and summer conditions. Moreover, windows also provide daylight and view to the outside and can be used to save energy for artificial lighting. Architects, engineers and builders are presented with the challenge of balancing all these different aspects in the design of future ‘nearly zero-energy’ buildings.

If the goals for fossil-free energy supply are to be achieved, the energy consumption in existing buildings also needs to be reduced. A large immediate potential for energy savings lies in the current building stock. In Denmark, 75% of all buildings were constructed before 1979, when the first significant tightening of insulation requirements in buildings was introduced (SD, 2013). Many of these buildings will need renovation in the coming years. Today, however, very few energy-saving measures are being applied in connection with the major renovations of existing buildings. Furthermore, due to the lack of attractive options for financing the investments, current renovation practice tends to focus on the replacement of single building components based on a do-it-yourself approach (Tommerup et al., 2010).

1.1 Aim and objective of research

The aim of the research work in this thesis is to contribute to the development of low-energy residential buildings with good indoor environment by providing architects, engineers and builders with recommendations and useful tools for the design of new residential buildings and the renovation of existing residential buildings. More specifically, the focus is on providing recommendations with respect to window design in new buildings, but they could also be used when major renovation includes the replacement of the existing façade. The research in this thesis provides insight into the interrelationship between various window parameters, and how these affect energy performance, daylight and thermal indoor environment. However, it was not the aim of the research work to find an optimal combination of these window parameters, but rather to quantify their performance based on integrated simulations of energy use and indoor environment.

Secondly, the interaction between energy use and indoor environment needs to be taken into account early in the design process if we want to design 'nearly zero-energy' residential buildings with a healthy indoor environment. The literature study showed that many of the simulation tools available today are either too difficult to use in the early design phases or are very easy to use but are unable to accurately predict energy use and indoor environment. That is why the second objective of the research work in this thesis was to provide a simplified tool for assisting architects, engineers and builders in predicting energy savings and indoor environment and help them with selection of an optimal window design in the early design phases.

Thirdly, knowledge is needed on how to update the existing building stock to low-energy standard. If existing buildings are to be renovated to this standard at a reasonable price, there is a need for a more integrated approach and the application of the full range of technical solutions (Haavik et al., 2010). Furthermore, to speed up renovation of the existing building stock and in particular single-family houses, house owners need help in the design and decision-making process. Therefore, this thesis recommends an ideal full-service concept in the form of one-stop-shopping (one-person contact), which includes all the steps necessary for the renovation.

1.2 Scope

The research for this thesis was carried out from a Danish perspective using the Danish climate and building tradition as a reference. However, Denmark has a climate that is comparable to several other north- and mid-European countries, so the results could also be used in these countries.

The focus in the thesis is on residential buildings, and more specifically on single-family houses, because they account for 74% of the total energy use in the Danish building stock (DEA, 2011). With regard to renovation, the main focus is on the segment of houses built in the period between 1960 and 1980, and houses built before 1930.

Furthermore, where I speak of energy use, focus is on reduction of the energy required for space heating because it is the majority of the energy used in single-family houses. Cooling is not evaluated because it is not used as standard in building practice in Denmark. Instead, the thermal indoor environment has been evaluated. Moreover, the visual indoor environment (use of daylight) is included. The quality of both the thermal and the visual indoor environment influences a building's energy use, so understanding how they relate to each other holds the key to the design of 'nearly zero-energy' buildings with a good indoor environment. Other aspects such as atmospheric and acoustic environment are not specifically considered but are important for a holistic view.

1.3 Hypothesis

The main hypothesis investigated in this research work is that:

Low-energy single-family houses can be designed with a window size in the different façades that is optimal from energy perspective, while at the same time providing enough daylight and a good thermal indoor environment.

The following sub-hypotheses, SH1-SH4, support the main hypothesis and cover the key aspects indicated in the aim and objective of this thesis.

SH1 *By designing low-energy single-family houses with an even window distribution where the window-to-floor-area is the same for each room, it is possible to position windows in the façade with considerable architectural freedom without compromising on the thermal indoor environment and space heating demand.*

SH2 *In new low-energy single-family houses, a window design with a minimum energy use for space heating and good thermal indoor environment can be freely chosen based on daylight requirements for each room.*

SH3 *A tool that is based on simplified methods for the calculation of thermal indoor environment and space heating demand in the early phases of the design process can provide results that are fast and accurate enough for decision-making on the selection of windows.*

SH4 *A one-stop-shopping or full-service renovation package can guide the homeowner to more qualified decision-making and optimal renovation.*

The research to investigate the sub-hypotheses is reported in the main body of this thesis and in four papers, referred to in the text as Papers I-IV. The papers are appended at the end of this thesis.

Paper I discusses the influence of window size, type and orientation on space heating demand and thermal indoor environment by comparing a window design with an even distribution (same window-to-floor-area in each room) with a traditional window design with large south-oriented windows for a single-family house constructed in accordance with current and future energy requirements. Furthermore, the influence of the thermal zone configuration on the prediction of space heating demand and thermal indoor environment and therefore on the choice of window design was also investigated.

Whereas in Paper I the analyses considered a whole building, investigations in Paper II were performed at room level and also include the aspect of daylighting. The intent of Paper II was to provide insight into the interrelationship between various window parameters (glazing area, orientation, U-value, g-value and visual transmittance) and their influence on space heating demand, thermal indoor environment and daylight in rooms representing geometries typical for single-family houses with a view to selecting a good window design as a starting point in the early design phases. However, this relationship depends on many factors, including the particular building and its energy system, so a simplified tool that can be used in the early design phases for the prediction of space-heating demand, thermal indoor environment and, to some extent, the use of daylight is presented in Paper III.

The tool described in Paper III can be used for the design of windows in both new buildings and for the renovation of existing single-family houses. The topic of renovation of existing single-family houses is discussed in Paper IV, where a method for renovation based on an ideal concept of a full-service package is proposed. This paper also discusses the combination of technical renovation solutions targeted at specific groups of single-family houses depending on the period of their construction.

1.4 List of publications

Publications included in the thesis

I. Vanhoutteghem, L. & Svendsen, S.
Modern insulation requirements change the rules of architectural design in low-energy homes.
Submitted to Building and Environment.

II. Vanhoutteghem, L., Skarning, G. J. C., Svendsen, S., Hviid, C.A.
Impact of window design on energy, daylight and thermal indoor environment in a nearly zero-energy house.
Submitted to Energy and Buildings.

III. Vanhoutteghem, L. & Svendsen, S.
WinDesign: a simple calculation tool for selection of windows in residential buildings.
Submitted to Applied Energy.

IV. Vanhoutteghem, L., Tommerup, H., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.
Full-service concept for energy efficient renovation of single-family houses.
Proceedings of the 9th Nordic Symposium on Building Physics - NSB 2011, Tampere, Finland, May 29–June 2 2011, pp. 1323–1330.

Additional publications not included in the thesis

Additional research studies were carried out during the 3-year PhD project 'Method for design of low-energy type houses based on simulations of indoor environment and energy use'. The research work listed below is not reported in this thesis for one of three reasons: because the investigations were not part of the core of the dissertation topic (studies *g* and *h*), or the results have already been included in the publications (publications *e – f, i* and *j – l*), or I was not the main author of the publication (articles *a – d*).

Contribution to journal articles

a) Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S., Svendsen, S., Vanhoutteghem, L., Ala-Juusela, M., Paiho, S. Business models for full service energy renovation of single-family houses in Nordic countries. In press at Applied Energy, http://dx.doi.org/10.1016/j.apenergy.2013.01.010.

Contribution to peer-reviewed conference articles

b) Hansen, S., Vanhoutteghem, L. 2012. A method for economic optimization of energy performance and indoor environment in the design of sustainable buildings. Proceedings of the 5th International Building Physics Conference, IBPC2012, Kyoto, Japan, 28-31 May 2012, 741-747.
c) Mlecnik, E., Paiho, S., Cré, J., Kondratenko, I., Stenlund, O., Vrijders, J., Haavik, T., Aabrekk, S., Vanhoutteghem, L., Hansen, S. 2011. Web Platforms Integrating Supply and Demand for Energy Renovation. 2011. Proceedings of the 4th Nordic Passive House Conference, PHN11, October 17-19 2011, Finland.
d) Haavik, T., Tommerup, H. M., Vanhoutteghem, L., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Aabrekk, S.E. 2010. Renovation of Single-Family Houses – An Emerging Market. Proceedings of Sustainable Community – buildingSMART, SB10, September 22-24 2010.
e) Tommerup, H. M., Vanhoutteghem, L., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.E. 2010. Existing Sustainable Renovation Concepts for Single-Family Houses. Proceedings of Sustainable Community – buildingSMART, SB10, September 22-24 2010.
f) Ala-Juusela, M., Paiho, S., Tommerup, H. M., Vanhoutteghem, L., Svendsen, S., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.E. 2010. Successful sustainable renovation business for single-family houses. Proceedings of Sustainable Community – buildingSMART, SB10, September 22-24 2010.

Contribution to research reports

g) Vanhoutteghem, L., Grøn, M., Wadsö. L. 2012. Energivejledninger - Mapning af danske og svenske vejledninger målrettet energiprojektering. Interreg IV project report.
h) Vanhoutteghem, L., Grøn, M., Møndrup, T. 2012. Pilot projects Activity 5 - BIM as a tool for verification of different national requirements. Interreg IV project report.

i) Vanhoutteghem, L., Svendsen, S. 2011. Documentation of Calculation Program and Guideline for Optimal Window Design. DTU BYG technical report SR-11-0.
j) Vanhoutteghem, L., Tommerup, H. M., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.E. Sustainable renovation concepts for single-family houses. 2011. Rapport in series: Nordic Call on Sustainable Renovation NICe, Nordic Innovation Centre.
k) Tommerup, H. M., Vanhoutteghem, L., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.E. Existing Sustainable Renovation Concepts. 2010. Rapport in series: Nordic Call on Sustainable Renovation NICe, Nordic Innovation Centre.
l) Vanhoutteghem, L., Tommerup, H. M., Svendsen, S., Paiho, S., Ala-Juusela, M., Mahapatra, K., Gustavsson, L., Haavik, T., Aabrekk, S.E. Analysis of promising sustainable renovation concepts. 2010. Rapport in series: Nordic Call on Sustainable Renovation NICe, Nordic Innovation Centre.

1.5 Structure of the thesis

The research work presented in this thesis is structured in seven main chapters. An introduction giving the objective and scope of the research work is found in this chapter and the background for the research work is presented in *Chapter 2*. I have chosen not to include general background knowledge of building physics and the energy and daylights aspect of windows, so readers not familiar with the topic of this thesis are referred to a review of this topic in research work carried out by Bülow-Hübe (2001) and more recently by Persson (2006). The methodology of the research presented here is described in *Chapter 3* and the general research results are presented in *Chapter 4*. These results are discussed in *Chapter 5*, and finally *Chapter 6* draws conclusions from the research and gives recommendations for future work.

2 Background

This chapter starts with a brief description of the context for the research work for this thesis and then goes on to suggest some general thoughts on the design of new low-energy building and renovation practice in existing buildings. Furthermore, a short description on performance requirements and the use of building simulation for documentation of building performance is given.

2.1 Context

Due to the increasing concern about climate changes caused by CO_2-emissions from fossil fuels, a general reduction in total energy consumption is needed. The building sector can play an essential role in achieving this because the energy used for heating and cooling in buildings represents between 30- 40% of the total energy consumption in Denmark and the European Union (ENS, 2012, EC, 2010). To improve energy efficiency in the building sector, the European Union introduced the Energy Performance of Buildings Directive (EPBD) in 2002 (EU, 2002). The latest version of this directive (EU, 2010) states that all new buildings should have 'nearly zero' energy consumption by 2020. To comply with the principles of the EPBD, the Danish government has agreed on a reduction of energy consumption in new buildings by at least 25% in 2010, in 2015 and in 2020, which would result in a total reduction of energy consumption in new buildings of at least 75% by 2020 compared to 2006 levels (DEA, 2008). In the current building code (DEA, 2013), this is reflected by the introduction of an energy framework for standard buildings (Class 2010) and the additional definition of two optional frameworks for low-energy buildings (Class 2015 and Class 2020), see also *Section 2.4.1*. Moreover, the Danish government has adopted a vision for fossil-free energy supply saying that Denmark is to become independent of fossil fuels by the year 2050. To support this vision, by 2035 all electricity and heat production in buildings is to be based on renewable energy sources (DG, 2011). If we are to achieve this, in addition to newly built 'nearly zero-energy' buildings, it is very important to consider the renovation of the existing building stock to an acceptable energy standard.

We spend 90% of our time indoors (Leech, 2002), so ensuring a good indoor environment is another key aspect in designing new 'nearly zero-energy' buildings and renovating existing buildings. Several studies have documented that the indoor environment affects people's well-being, health and productivity in offices (Wargocki et al., 2002, Wargocki et al., 2007, Webb, 2006). Recently, there has been renewed attention to the integration of aspects of the indoor environment in the design of residential buildings as part of a movement towards sustainable buildings with a focus on user well-being. 'Active houses' (AHA, 2013a), for example, are to be designed so that they allow for optimal daylight and attractive views to the outside while ensuring a good thermal indoor environment and low energy consumption, and this without having negative environmental impact.

2.2 An approach to the design of low-energy buildings

According to the recast of the Energy Performance of Buildings Directive (EPBD), 'nearly zero-energy' buildings must be constructed to have a very high energy performance (low-energy), and their energy needs should be covered to a significant extent by energy from renewable energy sources (EU, 2010). However, it is up to each of the member states to define what 'a very high energy performance' and 'a significant extent' of renewable energy exactly means (Atanasiu and Kouloumpi, 2013). As a result, different national or cross-border definitions, concepts and schemes for the labelling and certification of low-energy buildings are found all over Europe (IEE, 2010). One well-known example is the 'Passive house' standard defined by the Passive House Institute in Darmstadt, Germany (PHI, 2013). Other examples are the Swiss 'Minergie-P' standard (SE, 2013) and concepts such as 'very low-energy houses' (IEE, 2010), 'net zero energy buildings', 'zero emission buildings' and 'plus-energy buildings'. A recent concept targeted at single-family houses is the previously mentioned definition of 'Active houses' (AHA, 2013a).

Alongside political developments, recent years have seen increased focus on research in the field of low energy houses. This has resulted in several development and demonstration projects both in Denmark and abroad. For example, some of the first passive houses in Denmark were the result of the development project 'Comfort Houses' (KH, 2013). To reflect local architecture and see how the 'Passive house' standard could fit into the Danish building tradition, the 10 houses in the project each have different architectural expressions. Focus is also on providing high level of comfort. At a European level, similar projects are the early CEPHEUS project (Cost Efficient Passive Houses as European Standards, Schnieders and Hermelink, 2006) and the PEP project (Promotion of European Passive houses, Smeds and Wall, 2007). More recently, six demo-houses were built in five European countries as part of the 'Model Home 2020' project, which was aimed at developing climate-neutral buildings with a high level of livability (MH, 2013). One of the houses, called 'Home for life' was constructed in Denmark, also on the basis of the 'Active house' specifications (AHA, 2013b).

These projects have shown that low-energy buildings can be constructed in many different ways. New products are being developed all the time and products are becoming more energy-efficient. However, common to the design of low-energy buildings is to reduce heat losses by using a well-insulated and airtight building envelope with minimal thermal bridges, the installation of energy-efficient ventilation with heat recovery, and the use of energy-efficient windows to achieve passive solar gains. In some cases, opportunities to utilize alternative energy sources and renewable energy production on site are also integrated, e.g. the use of solar thermal collectors, heat pumps, and photovoltaics. But it is important that energy consumption is reduced as much as possible before using renewable energy to cover the remaining demand in accordance with the Trias Energetica concept (Dokka and Rødsjø, 2005).

2.2.1 Role of passive solar design

The use of passive solar gains can meet a substantial share of the heating demand, even in cold climates. In a building heated by passive solar gains, windows are oriented and arranged so as to optimize the use of solar gains. Due to a historical focus on minimizing heating demand in residential buildings, and the popularity of large window areas following the development of energy-efficient windows, passive solar design is commonly used in low-energy architecture (Marsh, 2011). In accordance with this, one widely accepted way of building low-energy residential buildings has been to have large windows facing south to gain as much solar heat as possible on the south side and smaller windows to the north to minimize losses on the north side. This approach has also been supported by research on the selection of appropriate window size (Inanici and Demirbilek, 2000, Jaber and Ajib, 2011, Albatici and Passerini, 2011) and the thermal performance of various types of window (Hassouneh et al., 2010, Gasparella et al., 2011), which has shown that orienting the largest window area to the south gives the lowest space-heating demand. Moreover, these research studies also indicated that, depending on the glazing type, the overall energy needed for heating decreases with an increase in window size to the south and that southern windows should be as large as possible if the right glazing is used.

But there is a problem. Some of these studies were made for less well-insulated buildings, or for less energy-efficient windows, or for regions with a different climate. If only energy-efficient windows are used (Bülow-Hübe, 2001), the insulation level in low-energy buildings means that it is no longer so important to use large south-oriented windows to reduce space-heating demand (Persson et al., 2006, Morrisey et al., 2011). On the contrary, attention should be focused on the risk of overheating. Due to the reduction in heat losses, the heating season in low-energy buildings is shorter and solar irradiation through windows has a much smaller effect on heating demand than on cooling demand (Gasparella et al., 2011). The need for cooling, however, can be reduced by a more careful design.

Experience from demonstration projects in Denmark and Sweden, whose climate is similar to the Danish climate, has shown that active use of venting and external solar shading are needed to prevent overheating and should be integrated early in the design of low-energy residential buildings (Janson, 2008, Larsen, 2011, Brunsgaard, 2012). The use of external solar shading, however, is not common for residential buildings in Denmark. Often alternatives, such as large overhangs and interior solar shading are used, but it has been demonstrated that these do not provide enough protection against overheating in low-energy buildings (Janson, 2008, Larsen, 2011). However, the user plays an important role in relation to the active use of venting and of external solar shading which is often dynamically controlled. Users have a tendency to override these systems, which can have significant impact on the indoor environment and energy consumption, see also *Section 2.5.5*. So it is important for the operation of low-energy buildings that the user is well-informed and knows the consequences of his actions (Isaksson, 2009, Brunsgaard et al., 2012)

2.2.2 Daylight design in low-energy buildings

From an architectural point of view, windows are primarily used in buildings for visual contact between the inside and outside and as a source of daylight. Daylight is the preferred source of lighting for humans (Loe, 2009), and utilizing daylight can reduce the energy used for artificial light. Studies have shown that the electricity consumption for artificial lighting corresponds to 7-10% of the total energy consumption in a typical home today (Gram-Hanssen, 2005). At the same time, daylight is a component of solar radiation, which in turn influences a building's energy performance and thermal indoor environment. Daylight is important for how we feel (Webb, 2006), so an optimization of window design should not be only about the energy needed for heating and cooling.

As discussed above, low-energy houses often have large south-oriented window areas to utilize solar gains and small window areas in north-oriented rooms. This can result in dark rooms in the northern part of the house as well as a risk of overheating, and problems with glare in south-facing rooms, if there is no solar control in the form of venting and solar shading. And if there is solar shading, a balance has to be found between the control of direct solar radiation, the availability of daylight, and the view outside. Investigations of the effect of window size on energy use in passive houses in Sweden have shown that instead of this traditional way of building passive houses, it should be possible to enlarge the north-facing window area and get better lighting conditions (Persson et al., 2006). However, results from the NorthPass project (Peuhkuri, 2010) indicate that it is not possible, yet with very good windows, to get a better heat balance in North European countries when using larger window areas for the north orientation. We investigate this question in more detail in Paper I and II.

Furthermore, the use of energy-efficient windows means that glazings have lower light transmittance, and the use of more insulation means thicker walls and reduced daylight penetration. So, the challenge in the design of low-energy buildings is to find a window design that provides sufficient daylighting and solar shading and reduces energy consumption but also provides a high quality thermal indoor environment. Due to the renewed focus on user well-being in the design of buildings, some examples can be found today of residential buildings where daylight design has been considered from the beginning (AHA, 2013a, MH, 2013, KH, 2013). For example, the 'Home for life' house in Denmark was designed with a window-to-floor ratio of 40% to achieve an average daylight factor of 5%. This is about twice the window-to-floor area usually used in single-family houses. Even so, the overall thermal indoor environment is good, due to the special attention given to solar control using dynamic solar shading and ventilative cooling by natural ventilation (Foldbjerg and Asmussen, 2013). Another example is the design of a the 'Comfort Houses' in which the glazing area was selected to provide a daylight factor of 2% all the way to the back of primary rooms. Here, however, there were problems with overheating because no solar control of any kind was provided (Larsen, 2011). This implies that the design of future low-energy residential buildings could still benefit from more detailed investigations of window design and its influence on daylight availability, thermal indoor environment and energy consumption. This topic is explored in Paper II.

2.2.3 Choice of window design

From the above, it can be concluded that many aspects need to be taken into account when choosing a window design for low-energy buildings. Moreover, it is important to select the right window design in the early stages of the design process. Since the selection of the right window design is not usually immediately obvious, several window energy rating systems (WERS) have been developed in different countries (Carpenter et al. 1998, Maccari and Zinzi, 2001, Nielsen et al., 2000, Duer et al., 2002, Karlsson et al., 2001) to assess the energy performance of the many existing types of window and to encourage the development of new window products. There are several ways of establishing a WERS, but most of them consider different window properties such as thermal transmittance (U-value) and total solar energy transmittance (g-value) and are based on estimation of the energy balance or net energy gain (NEG) of windows installed in small residential buildings. However, a WERS can also be adapted for office buildings and include, for example, energy savings from the utilization of daylight (Tian et al., 2010).

In Denmark, the NEG is calculated over a fixed length of the heating season in a reference single-family house. To calculate the solar heat gain, a simple model for the dependency of total solar transmittance (g_w) on the incident angle has been used and is assumed the same for all types of glazings. The NEG formula is described as follows (Nielsen et al., 2000, Duer et al., 2002):

$$NEG = I \cdot g_w - D \cdot U_w \qquad (1)$$

According to the calculations performed by Nielsen et al. (2000) based on the Danish Reference Year (ref), $D = 90.36$ kKh and $I = 196.4$ kWh/m^2 for a heating season from 24/9-13/5. In future residential buildings, however, the heating season will be shorter. Therefore, it is suggested that $D = 74$ kKh and $I = 116$ kWh/m^2 when calculating NEG in well-insulated buildings (EB, 2011). The Danish Building Code indicates certain maximum values for the calculated NEG (see *Section 2.4.1*).

While NEG might seem a practical tool for evaluating the energy performance of windows and allow easy and quick comparison of various windows, the energy performance of a window depends not only on the window properties, but also on their interaction with the whole building. Experience has shown that windows with high g-values are favoured by the calculation of NEG over the heating season. This could result in overheating problems and a need for cooling in low-energy buildings outside the heating season. Furthermore, even if the calculation of NEG can be adapted to take account of cooling demand, the potential overheating problems are difficult to define because they depend on the ventilation rate, the thermal mass of the building, etc. Since the choice of the best window for an actual building is a complicated design decision (Schultz and Svendsen, 1998) that should include both evaluation of energy savings and thermal indoor environment, it might be better to use building simulation to evaluate how a window performs in an actual building. In this thesis, a tool that includes both evaluation of NEG and simulation of windows in an actual building is suggested to help with the selection of window design in residential buildings.

2.3 Current renovation practice

In addition to new building design, the renovation of existing buildings will play a major role in achieving Denmark's target of phasing out fossil fuels and supplying all buildings using renewable heat sources by 2035. In this section, first an overview of the energy-saving potential in the Danish building stock is given with the focus on single-family houses. Afterwards, barriers and incentives for the energy renovation of single-family houses are discussed. The barriers described bear in mind that most single-family houses in Denmark are privately owned.

2.3.1 Potential for energy savings in the existing building stock

A large savings potential has been identified in the existing building stock. Recent building stock analysis (Kragh and Wittchen, 2010) shows that the energy demand for heating and hot water in the Danish building stock can be cost-efficiently reduced by 52% (81PJ/yr.) to 73% (116PJ/yr.) if the existing building stock is renovated to the level of new buildings today or to the requirements set in the Danish Building Code for buildings constructed in 2015, or later. Similar, Tommerup (2004a) found a profitable savings potential of energy demand for heating and hot water of about 80% over a 45-year period (until 2050) in the Danish residential building stock by assuming that the entire existing residential building stock will either be replaced with new buildings or thoroughly energy-renovated to the energy requirements applicable for new buildings. Both studies also showed that the greatest energy savings could be obtained in the category of single-family houses (including terraced houses). Within this category, the largest energy saving potential lies in detached single-family houses built before 1930 (old farm houses) and those built in the 1960s and 70s (Vanhoutteghem et al., 2010 and Wittchen, 2009). The large potential for energy savings in houses from the 1960s and 70s is due to the combination of a poor energy standard and the large number of such houses. Around 450,000 standard detached single-family houses were constructed during this 20-year period, corresponding to 38% of all detached single-family houses existing today (SD, 2013).

Many of these single-family houses have already been renovated with a new kitchen/bathroom, replacement of the existing roof and additional roof insulation, and/or new windows (BB, 1998). However, very few of these renovations were implemented to save energy. Some demonstration projects have shown that these renovated buildings still need significant upgrading to match the standards for new buildings (Tommerup, 2004b, PLE, 2011). The case studies included in this thesis (see *Section 4.3.3*) show that, with a complete energy renovation of the building envelope and building systems, primary energy savings of up to 70-80% could be obtained and a total energy consumption corresponding to the energy consumption in new buildings today could be reached. This has been confirmed by a recent demonstration project illustrating a complete energy renovation of a single-family house from 1975 up to new building level (PLE, 2011). Similar primary energy savings have also been demonstrated in case studies in other countries (Vanhoutteghem et al., 2010).

2.3.2 Barriers to renovation

Investors often find energy efficiency investments in single-family houses risky and economically unattractive (IEA, 2008, BPIE, 2010). Moreover, house owners typically give low priority to energy renovation, often due to lack of knowledge and uncertainty about the consequences (Nair et al., 2010, Mahapatra et al., 2013). However, recent investigation into the attitude of private house owners of single-family houses reveals that interest in energy renovation is increasing (Bolius, 2013) but that the cost is seen as the main barrier to energy renovation, especially among younger house owners. Since energy renovation typically involves relatively large investment costs, it is important for renovation to be based not only on energy savings but also linked to measures to improve the thermal comfort and architectural quality of the house. Furthermore, availability of skilled work force, financing mechanism, and above all the awareness, interest and demographic characteristics of the occupant influence the form and degree of renovation of buildings.

Another point influencing productivity and scope in energy renovation is the fact that market for single-family house renovation is dominated by do-it-yourself work and a craftsman-based approach (Tommerup et al., 2010, Vanhoutteghem et al. 2010). House owners do not usually use professional labour until the renovation work is for more than 25,000 DKK (Bolius, 2013). And in the case of a renovation, the house owner will rarely hire a consultant, but instead rely on the advice of the craftsman hired to carry out the renovation. As such, the craftsman has significant influence on the house owners' decision (Nair et al., 2010, Mahapatra et al., 2013,). However, craftsmen are usually very cautious about suggesting and pushing far-reaching energy renovation measures and often offer only individual solutions that are in their own field (Bechmann and Engberg, 2010). Even when several solutions are sourced from different companies, a house owner faces the difficulty of coordinating the activities of all the actors and has to take the risk and responsibility for the renovation project. To stimulate more thorough and holistic energy renovation, it should be easier for the house owner to start a renovation. Not only should the construction industry recognize the importance of cooperation and communication between different types of actor, they should also provide house owners with guidance and the right information in each decision step of the renovation process (Bechmann and Engberg, 2010, Mlecnik et al., 2012). Implementing one-stop-shop business models for the energy renovation of single-family houses, where a single actor can offer a full-service package including consulting, contract work, follow-up, financing, and operation and maintenance, could provide the house owner with a holistic and long-term solution for a thorough energy renovation. This is explored in Paper IV.

2.3.3 Incentives to stimulate energy renovation

As mentioned, few investments in renovation are made to save energy even though there is a large savings potential in the Danish building stock. This is mainly due to the lack of attractive options for financing the investments, cheap management solutions for the building renovation project (especially with regard to single-family houses), and ‘picking of the lowest hanging fruits’. Several initiatives in Denmark have discussed how to stimulate and create better energy renovation (Jensen, 2009, TB, 2012). They found that legislation in the form of requirements in the building code (see *Section 2.4.1*) or for the use of an energy label is not enough to achieve the energy savings potential in buildings. There has been little interest in energy labelling of buildings for sale, especially in privately owned single-family houses, even though it is a requirement. In its current form, the energy label is also rarely seen as an incentive for thorough energy renovation, even though it has been shown to have an effect on house prices (Hansen et al. 2013). Changes in legislation need to be complemented by incentives, for example economic incentives to encourage the building sector to invest in very low-energy design, information campaigns to change attitudes towards energy renovation, sharing experiences from demonstration projects, and specialised training aimed at all stakeholders.

2.4 Performance requirements

Buildings should be designed and constructed according to user needs and provide occupants with a comfortable indoor environment. To decrease energy consumption, society has also introduced requirements in building codes and standards to regulate the performance of buildings. This section introduces the Danish building code’s performance requirements for residential buildings with regard to energy use, thermal indoor environment, and use of daylight in relation to other standards. The topic of cost is also briefly touched upon because this plays an important role in design decisions in new buildings and is often the most decisive factor in renovation projects.

2.4.1 Energy requirements in the Danish Building Code

Over time, the requirements in the Danish Building Code (DEA, 2013) have been tightened several times to reduce energy consumption in buildings. Unlike earlier requirements at component level in terms of limits to U-values, calculation of the whole building’s energy consumption was introduced as an alternative in 1995. With the adoption of the EPBD in 2006, this became a mandatory target in the form of the definition of a framework for the whole energy performance of a building at a more holistic level. This gives architects and engineers more design freedom but also requires a better understanding of the interplay between the different building components. Some requirements for maximum U-values are still included in the building code, but these are most often used for extension, conversion and renovation projects in existing buildings.

In 2010, an energy performance framework for standard buildings (Class 2010), and two optional frameworks for low-energy buildings (Class 2015 and Class 2020) were introduced in the Danish Building Code (DEA, 2013). The frameworks are denoted as energy Class 2010, 2015 and 2020 after the year they became or will become the current requirement. New buildings should be designed so that their primary energy consumption does not exceed the energy performance framework, see Table 1. The energy performance framework includes the energy usage for energy supplied for heating, cooling, ventilation, domestic hot water, and (for non-residential buildings only) lighting.

Table 1 Energy frameworks and the primary energy factors for their calculation.

	Energy framework [kWh/m²K pr. year]		**Primary energy factors [-]**		
	Residential buildings	**Offices, schools, institutions, etc.**	**Electricity**	**Heating (oil, gas)**	**District heating**
2010	52.5+1650/A [1)]	71.3 + 1650/A [1)]	2.5	1	1
2015	30 + 1000/A [1)]	41 + 1000/A [1)]	2.5	1	0.8
2020	20	25	1.8	1	0.6

1) A = heated floor area

To calculate the energy performance framework, various types of energy supply are weighted, i.e. multiplied by their respective primary energy factor. Due to the expected development in district heating, wind power, and renewable technologies, the primary energy factors for the different types of energy supply change with time and are different for the different energy performance frameworks.

For renovation, individually renovated building components only have to meet U-values stated in the building code as far as this is technically, functionally and economically feasible. If it is impossible to meet these requirements in a cost-effective way or it would result in using solutions that can create moisture problems, less extensive work that can reduce the energy consumption should be implemented. In conclusion, when it comes to renovation, there is no actual legal requirement to motivate energy renovation. However, when building components are replaced or in extension or conversion projects, the U-values given in the building code must be met regardless of their cost-effectiveness.

For windows, requirements in terms of maximum allowable net energy gain (NEG) are also included in the building code, see Table 2. These are valid for windows in new buildings and when replacing existing windows, and should be calculated on basis of a reference window size of 1.23m x 1.48m. For a definition of NEG, see *Section 2.2.3*.

Table 2 Requirements for NEG of windows depending on the energy framework [kWh/m²K pr. year]

Energy framework	**2010**	**2015**	**2020**
Side-lit windows and glass walls	NEG ≥ 33	NEG ≥ -17	NEG ≥ 0
Roof windows	-	NEG ≥ -10	NEG ≥ 10

Documentation of energy performance

In Denmark, a calculation of the energy framework in the standard calculation tool Be10 (DBRI, 2013a) is required from any project team seeking a building permit. Calculations in Be10 are based on the method and input parameters for standard building practice as defined in SBi-anvisning 213 (Aggerholm and Grau, 2011). The calculation method specified in SBi-anvisning 213 is based on method 1 for calculation of heating and cooling as specified in EN ISO 13790 (CEN, 2008) and uses monthly mean values of weather data for the calculation of the energy framework. Implementation of the method in Be10 is based on a single-zone model in which overheating is represented as the electricity use from a mechanical cooling plant needed to cool rooms when their air temperature exceeds 26°C. The use of the single-zone model and the assumptions in the calculation method require little model input and simulation time, but can result in an underestimation of energy use and the need for cooling.

2.4.2 Thermal indoor environment

In 2006, an energy performance framework was introduced which takes into account several categories of energy consumption such as heating, cooling and ventilation, yet there is still an architectural tendency to focus on solutions that minimize the energy needed for heating in residential buildings. This can introduce overheating and an increased need for cooling in low-energy residential buildings. To ensure that these buildings are designed with a healthy indoor environment that takes conditions in both summer and winter into account, requirements for documentation on the thermal indoor environment in future residential buildings were added to the building code.

The thermal indoor environment can be evaluated under different conditions. In the European standard EN 15251 (CEN, 2007a), various categories and criteria for the evaluation of thermal indoor environment are suggested, such as predicted percentage of people dissatisfied (PPD), predicted mean vote (PMV), and ranges for indoor temperature (fixed or dynamic based on running mean outdoor temperature). Table 3 illustrates the various categories of fixed temperature ranges in primary rooms in residential buildings.

Table 3 Categories for temperature ranges in residential buildings (CEN, 2007a).

Category	Temperature range for heating (°C)	Temperature range for cooling (°C)
I	21-25	23.5-25.5
II	20-25	23-26
III	18-25	22-27

The Danish building code refers to the performance requirements for the evaluation of thermal indoor environment as specified in the Danish standard DS 474 (DS, 1993). This standard allows the design assumptions of having a winter temperature between 20-24ºC and summer temperature between 23-26ºC (similar to requirements for category II in EN 15251) to be exceeded in extreme conditions.

As such, it has been defined that in critical rooms in residential buildings constructed in accordance with energy classes 2015 and 2020, the indoor temperature should not exceed 26°C for more than 100 hours and 27°C for more than 25 hours during the year (DEA, 2013). Apart from the aspect of overheating, it is also stated that heating systems should be dimensioned so that winter comfort temperatures can be achieved.

Documentation of thermal indoor environment

Documentation of the thermal indoor environment should be based on weather data from the Danish Design Reference Year (DRY) (Jensen and Lund, 1995). For residential buildings, this can be based on a simplified calculation. In the standard calculation tool for documenting energy performance, Be10 (DBRI, 2013a), the amount of energy needed for cooling is used by many to evaluate the extent to which the thermal indoor environment is satisfactory. However, this does not allow for the assessment of excessive temperatures. So, a method for documenting thermal indoor environment based on a simplified approach is currently under development at the Danish Building Research Institute (DEA, 2013).

2.4.3 Daylight

Future buildings should be designed so that they allow for optimal daylight and attractive views to the outside while ensuring a good thermal indoor environment and low energy consumption. In residential buildings, no specific requirements for daylight are in place today, except for a functional requirement that primary rooms must be well-lit and that windows should be designed and positioned so that solar gains/radiation through the windows does not lead to overheating of the rooms or glare problems. For residential buildings designed in accordance with the energy framework 'Class 2020', however, a requirement for a minimum glazing-to-floor ratio of 15%[1] in primary rooms has recently been added to ensure better use of daylighting. This requirement could also result in a better distribution of window area in residential buildings, which could improve thermal indoor environment or increase robustness in terms of building orientation. These issues are also discussed in Paper I.

Evaluation of daylight

The requirements for daylight are expressed in terms of a minimum glazing-to-floor ratio and do not require documentation in residential buildings. For office buildings, these requirements are supplemented by the requirement for a minimum daylight factor of 2% in the working plane to ensure a reasonable level of daylight (DEA, 2013). The daylight factor is defined as the ratio of indoor daylight illuminance and the exterior horizontal illuminance outside the building calculated under standard CIE overcast sky conditions, so variations in daylight over time for different climates, locations and building orientations are not taken into account. Over the last decade, research in the field of daylighting has discussed the shortcomings of the daylight factor method (Mardaljevic, 2006, Reinhart et al., 2006, Mardaljevic et al., 2009) and suggested as an alternative the use of climate-based daylight modelling (CBDM),

[1] When side-lit windows with a light transmittance of 0.75 are used. If the light transmittance is lower, the glazing-to-floor ratio should be increased proportionally.

which provides daylight predictions under realistic sun and sky conditions based on available weather data. However, the daylight factor method is still used in guidelines and standards (AHA, 2013b, DEA, 2013, BS, 2009). Moreover, the use of CBDM requires expert knowledge or expert simulation tools, while the daylight factor method uses existing tools and requires less computation power. As a transition between the current practice of using the daylight factor method and the use of CBDM, Mardaljevic and Christoffersen (2013) have suggested the use of a slight modification to the daylight factor method that creates connectivity to the diffuse daylight access at a specific location. This is explored in Paper III and also compared with the use of CBDM and standard calculation of the daylight factor in *Section 4.1.2*.

Visual discomfort from glare can also be evaluated, but this was not included as part of the research work for this thesis because it is assumed that users can draw curtains to control glare, or adapt to glare by moving around in the room.

2.4.4 Cost

Cost is a very important parameter and is often decisive when planning a renovation. Energy-saving measures often result in large investment costs but reduce future costs for the operation of a building. Energy renovation can be stimulated by parameters other than energy savings, such as for example improved thermal indoor environment; but these are often difficult to quantify in economic terms. An economic evaluation of energy-saving measures should include not only all investment costs but also the total cost of operating the building during its lifetime. Furthermore, economic analysis can be used to compare alternative energy-saving measures and whether they are cost-effective.

Evaluation of cost-effectiveness

There are various criteria for assessing the cost effectiveness of energy-saving measures, such as simple payback time, net present value (NPV), and the cost of conserved energy (CCE) (Hermelink, 2009). The simple payback time is one of the most popular criteria used because it is readily comprehensible for non-economists. It is a fairly good tool for comparing different energy-saving measures with a short lifespan (up to 15 years), but is less suited as a basis for decisions that have consequences running 50–100 years into the future, since it does not take into account the lifetime of energy-saving measures (Hermelink, 2009). What is needed instead is a criterion that gives an indication of the net benefit of a long-term investment, such as net present value (NPV). The NPV of an energy-saving measure is determined as the difference between the present value of the cost savings due to the application of the energy-saving measures (e.g. operating cost, maintenance cost and replacement cost) and the present value of the investment costs. In the calculation of the NPV, all future cost savings are discounted at the time of investment and are accumulated to the investor's net benefit. Differences in the lifetime of measures should be taken into consideration by introducing the necessary reinvestments and the residual value of investments into the calculations at the end of the chosen calculation period (Tommerup and Svendsen, 2006). The CCE-method (Meier, 1983) is derived from the NPV method and gives the cost to save 1kWh of energy.

Usually, the results of the CCE coincide with results from NPV calculations. However the calculation of the CCE is slightly simpler and its interpretation is more readily comprehensible since the CCE simply indicates whether it is cheaper to save energy or to consume it because it is directly comparable with the cost of supplied energy. However, whichever of these criteria is used for the calculation of the cost-effectiveness of energy-saving measures, the cost-effectiveness of their implementation is often hard to prove, see also *Section 4.3.3*. But it should be borne in mind that energy-saving renovation measures not only save energy but can also improve the condition of a building and in turn increase its value. This aspect of the so-called "two-fold benefit" of energy-saving renovation measures can be dealt by introducing a coefficient of building rehabilitation or an energy renovation factor which states the share of the renovation work or investment that could be ascribed to energy-saving measures (Martinaitis, 2004, Tommerup and Svendsen, 2006).

2.5 Performance assessment

The definition of an energy framework for the performance of a building gives architects and engineers great freedom in the design process, and makes it possible to combine and vary many different design solutions. To meet the energy framework performance, assessment of the impact of these different design solutions is needed before buildings are constructed. Since the energy balance of a building is quite complex and is defined by many interdependent parameters, computer-aided building performance simulations play an important role in performance assessment (Peltormäki, 2009).

2.5.1 Using an integrated approach to performance assessment

Traditionally, most performance assessments are conducted late in the design (Petersen and Svendsen, 2010, Stumpf et al., 2011). However, many aspects of overall building performance depend on decisions made in the early design phases. Furthermore, it is well-proven that changes in design decisions and improvements of building performance are relatively easy to make in the early design phases, but become increasingly difficult as the building project develops (Jørgensen et al., 2009), see Figure 1. Costly changes can, however, be avoided if aspects such as energy use and indoor environment are considered from the early phases in the design process.

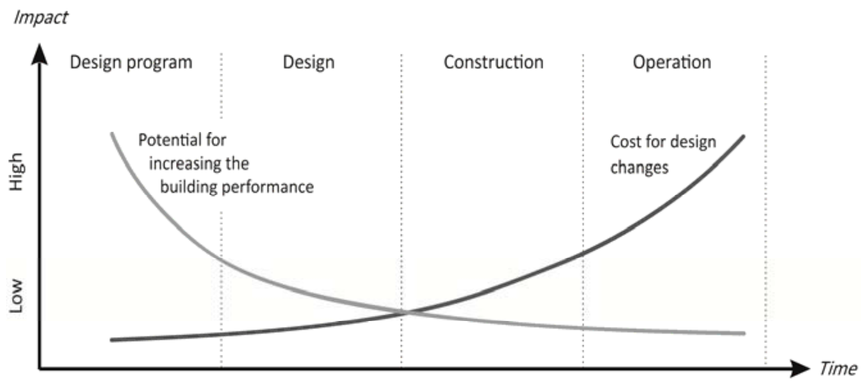

Figure 1: The range of options for changing the building design decreases significantly while the cost of design changes increases as the project progresses.

Several studies describe and analyse the potential benefits of using integrated simulation of energy use and indoor environment on the overall building performance, such as a reduction in total energy use and peak heating/cooling load (Lee et al., 1998; Laforgue et al., 1997) and improvements in the use of daylight and the thermal indoor environment (Franzetti et al., 2004). This calls for an integrated design process (IDP) where several actors are involved and collaborate from the early design phases (Petersen, 2011, Nielsen, 2012). Furthermore, there is a need for tools that can be used for the qualified evaluation of building performance in the early design phases (de Wilde, 2004, Petersen and Svendsen, 2010) and that can give a transparent overview of the impact of various design parameters on energy use and the indoor environment. In the following, an overview of various building simulation tools is given.

2.5.2 Simulation tools

There are many different tools for evaluating the performance of a building design. These range from user-friendly tools based on simplified calculation procedures to more advanced and sometimes more specialized tools using detailed calculation procedures. To evaluate building performance in the early phases of the design process, it is necessary to have a tool with simplified input and short simulation time. Simplified calculation procedures often use only a few input data describing the building and are also often limited to evaluating space-heating and cooling demand. Several simplified methods have been developed for calculation of space-heating and cooling demand, such as the degree-day method or the quasi-steady-state method as defined in EN ISO 13790 (CEN, 2008) and its predecessor EN 832 (CEN, 1998). Tools such as EPIQR (Wittchen and Aggerholm, 2000), Be10 (DBRI, 2013a) and TEKLA (Olofsson and Mahlia, 2012) are based on implementation of the quasi-steady-state method. There are also some simple and intuitive tools for calculation of daylight such as Daylight Visualizer (DV, 2013).

However, tools based on simplified calculation procedures are usually too limited to be of much use, even in the early design phases (Donn et al., 2012). But there are several simulation tools, such as iDbuild (Nielsen et al., 2008), that occupy the middle ground between tools using simplified calculation procedures and the very detailed simulation tools. These tools are capable of evaluating heating and cooling demands and indoor air temperatures based on simple dynamic modelling. Their advantage is that they still only require a low level of input but use dynamic calculations of heat flows and systems and can more easily be used in the early design phases.

More advanced tools, which integrate evaluation of energy use, thermal indoor environment and in some cases also daylight, are usually used later in the design process because they often require detailed input describing building geometry and construction, systems layout, and control strategies, and they require a significant level of expert knowledge. Furthermore, these tools also use detailed methods for calculation of (sub-)hourly energy flow, temperature profiles and system loads, such as finite difference methods, response factor methods, and the Fourier-method.

Examples of detailed simulation tools for the integrated evaluation of energy use and thermal indoor environment are BSim (DBRI, 2013b), ESP-r (ESRU, 2011), IDA ICE (EQUA, 2013), DEROB-LTH (Kvist, 1999), IESVE (IES, 2013) and EnergyPlus (USDoE, 2013a). Radiance (Ward and Shakespeare, 1998) and Daysim (Reinhart, 2011) can be used for detailed analysis and evaluation of daylight. Preferably, it should be possible to calculate effects on heating and cooling loads simultaneously with lighting energy savings. In EnergyPlus for example, it is possible to estimate the performance of various daylighting systems and control strategies and to evaluate the impact on the overall building energy use. Another approach is to link thermal simulation with daylight simulations. Radiance has, for example, been used in combination with ESP-r and TRNSYS (Fiksel et al. 1995). With the introduction of Building Information Modelling (BIM), interoperability between various tools has also increased with the number of tools.

Today, the calculation procedures of most advanced tools are also accessible from other programs, i.e. user-friendly shell programs can use the detailed calculation procedures of advanced tools. Examples are the use of eQUEST (DOE, 2013) and Openstudio (NREL, 2013) which are used as interfaces to EnergyPlus and Daylight 1-2-3 (Reinhart et al., 2007), which is based on Daysim for daylighting calculations and ESP-r for energy calculations. There are also examples of web-based services that can be used for the analysis of design alternatives, such as Green Building Studio (AutoDesk, 2013) based on DOE-2 simulations and EnergyPlus Example File Generator (USDoE, 2013c) based on EnergyPlus simulations.

2.5.3 Tools for the selection of window design

Most of the simulation tools mentioned above can be used indirectly for the evaluation of the effect of different window designs, but few allow an easy comparison of the effect of window designs varying in orientation, configuration and size. Many existing tools also require a high level of expertise, require a significant amount of time to prepare simulation inputs, and are often too difficult to learn or use in the early design phases, especially for the design of small-scale projects such as single-family houses. Some examples of tools created for supporting decisions with regard to window design are WinSel (Karlsson, 2000), GenWin (Khemlani, 1995), WinSim (Schultz and Svendsen, 1998), RESFEN (Sullivan et al., 1992 and Mitchell et al., 2005), COMFEN (Hitchcock et al., 2008) and EFEN (DBS, 2013). WinSel is based on a static model and does not allow evaluation of thermal indoor environment, but EFEN and COMFEN are based on the EnergyPlus simulation engine and allow evaluation of different window and façade designs, however, with focus on commercial buildings. Generally, in contrast to the many investigations of the physical parameters of windows, when it comes to simplified window selection tools for use in the early design stages, there has not been much detailed research. This is the topic of Paper III.

2.5.4 Tools for the evaluation of renovation projects

Most of the existing tools can also be used for the evaluation of renovation alternatives and the performance assessment of a renovation project. However, a renovation project is influenced by other design boundaries because it relies on the condition of an existing building. Obtaining exact information from an existing building can be difficult and time-consuming. Several tools, such EPIQR (Wittchen and Aggerholm, 2000), E-retrofit-kit (EV, 2013) and TOBUS (Flourentzou et al., 2002), have been specifically developed for the performance assessment of renovation projects, but these tools often use standard properties and generic input data to represent specific building types and their building components. In addition, a number of web-based tools have been developed. Energikoncept.dk (GI and Realdania, 2013) and TilstandsTjek (Rockwool, 2013) are examples of Danish online tools that can help building owners and consultants estimate the potential energy savings in connection with a renovation. Both tools are based on few input data and they cannot be used for detailed analysis. Furthermore, the measures proposed are often measures with a short payback time and will not result in the renovation of existing buildings to low-energy level. However, as they are freely available, they can help promote energy renovation.

2.5.5 Factors that influence the prediction of building performance

All too often, evaluation of the actual energy use in buildings shows that their performance is not as predicted, even when simulation has been an integral part of the design process. It has been shown that user behaviour plays an important role and can lead to variation in the energy consumption of Danish households by a factor of 3 or 4 (Andersen, 2009, Gram-Hansen, 2010). Similar findings have been reported in other countries (Guerra-Santin, 2009, Morley and Hazas, 2011). User behaviour also plays an important role in indoor environment. As mentioned, in low-energy buildings, the user may have a tendency to override automatic systems that prevent overheating, such as active use of venting and dynamically controlled external solar shading. It is therefore essential in each case to assess how much automation can be introduced before the user becomes dissatisfied (Hoes et al., 2009, Brunsgaard et al., 2012). Prediction of the performance of low-energy buildings could thus benefit from reliable data on user patterns and user interaction with controls. Otherwise it will result in buildings that can only operate under ideal design conditions (Donn et al., 2012).

Besides this, uncertainties due to execution, construction and actual performance of building systems can also have substantial influence on predictions of building performance. Furthermore, thermal zoning and interzonal airflow in modelling the performance of low-energy houses can have significant effect on predicted energy performance, thermal comfort and optimal design selection, because these houses are subject to high levels of periodic solar heat gains in certain zones (O´Brien et al., 2011). This is also considered in Paper I.

3 Method

This chapter describes the methodology of the research work conducted to test each sub-hypothesis (SH1-SH4). A more detailed description of the methods is given in Paper I-IV.

3.1 Window design in low-energy buildings

It can be concluded from the research described in the previous chapter that useful solar absorption through windows depends on many parameters and selecting a good window design is very difficult. Therefore, dynamic simulation tools were used to investigate the interrelationships between the various window parameters for side-lit windows, and how these affect energy performance and thermal indoor environment (Paper I), and daylight (Paper II). Parameter variations with regard to various window parameters were carried out at the level of the whole building (Paper I) and at room level (Paper II) for a design representing typical Danish single-family houses. Moreover, in some cases other factors, such as internal loads, were also studied in the thesis to put the results in perspective. And in Paper I, the influence of thermal zoning was also investigated.

Two different simulation tools were used. To evaluate the energy use for space heating and thermal indoor environment, the building simulation engine EnergyPlus (USDoE, 2013a) was used in combination with the tool jEPlus (Zhang, 2009, Zhang and Korolija, 2010), which is designed as a parametric shell program for use with EnergyPlus. EnergyPlus uses integrated simulation (simultaneous loads and systems) for accurate temperature and comfort prediction based on the heat balance model. Furthermore, it allows for a detailed treatment of solar radiation, which is especially important when carrying out state-of-the-art calculations on windows (USDoE, 2013b). The solar radiation transmitted was calculated by using the 'full interior and exterior with reflections' algorithm. In this algorithm, the amount of beam radiation falling on each surface of the zone (including floor, walls and windows) is included in the calculation. The properties and optical data of the window glazing and solar shading (Paper I) were derived in WIS (WinDat, 2006) and implemented in the EnergyPlus models. Analyses with regard to daylight were carried out using the RADIANCE-based daylighting analysis tool DAYSIM (Reinhart, 2011). DAYSIM was developed specifically for making annual simulations. In order to run these annual simulations efficiently, daylight coefficients (DC) are used (Reinhart & Herkel, 2000). This is an approach for running annual simulations in which the sky is subdivided into patches whose partial contributions are computed independently (Tregenza, 1983). In Paper II, the simulations were not based on annual simulations, but on the use of the CIE-overcast sky. The CIE-overcast sky is the same for different climates, locations and building orientations. In Paper II, however, the CIE-overcast sky was used to evaluate daylight based on a climate-dependent daylight metric that creates connectivity to the climate at a specific location (see *Section 4.1.2*). A comparison with additional results from annual calculations using realistic sun and sky conditions, i.e. climate-based modelling (CBDM) is also included in this thesis.

Both EnergyPlus and DAYSIM have been widely validated against real measurements in various research papers and are acknowledged simulation tools, so there is considerable knowledge about the methods they use. In this research, EnergyPlus and DAYSIM were used separately to investigate the influence of various window parameters on energy use, thermal indoor environment and daylight. A coupled computation of these aspects was not found necessary because only permanent solar shading solutions (reflected in g-value) were considered in Paper II on basis of findings in Paper I and savings in electricity use for artificial lighting were not included. Provided that rooms are designed for a high daylight performance with regard to comfort and health, the potential electricity savings for artificial lighting was considered a question of control systems and the usage of the building, rather than of window design. Furthermore, it was not the aim to investigate visual discomfort. Instead, it was assumed that users can draw curtains to control glare, or adapt to glare by moving around in the space.

3.2 WinDesign: a simplified calculation tool (for the evaluation of windows in residential buildings)

To evaluate the performance of a building design in the early design phases, it has been identified that there is a need for tools with simplified input and short calculation time that still give accurate enough results for qualified decision-making. Furthermore, there are very few tools for the selection of windows in residential buildings. Paper III introduces a user-friendly calculation tool based on simple input data. The tool, named WinDesign, was originally developed to assist engineers and architects during the process of selecting suitable windows for residential building design (Svendsen et al., 2008), but it can also be used more generally in the early design phases to predict building performance and carry out a quick parametric study.

The tool is organized in four steps, which together represent an analysis of how windows in a specific building design perform with regard to energy consumption, thermal indoor environment, daylight (based on electricity consumption for artificial lighting), and cost. The analyses in the steps gradually increase in level of detail and support design decisions throughout the design process. Calculations in the different steps are performed in accordance with methods 1 and 2 in the European standard EN ISO 13790 (CEN, 2008). Several reasons underlie the choice of the methods specified in this standard for the development of the WinDesign tool. First, the methods in the standard comply with the EPBD requirements for the definition and adoption of a common methodology for calculating energy consumption harmonized in all the different European countries (EU, 2010). Second, the methods rely on relatively few input data, which makes them suitable for use in the early design phases, and results in rapid simulations. As the aim of the developed tool is to be user-friendly, it has been built in Microsoft Office Excel 2007 using built-in functions and User Defined Functions (UDF) programmed in Visual Basic for Applications (VBA). In addition, the open Microsoft Excel and Visual Basic based programming makes it easy to adjust and process data and provides a familiar environment and platform for the user.

As an advance in the use of WinDesign and of analysis of energy use and thermal indoor environment as an integral part of the early design phases, the program has been provided with an import capacity from ArchiCAD, see *Section 4.2.2.*The tool has been used in a number of student projects and has been tested against results obtained with the detailed simulation program EnergyPlus. These comparisons and results from validation in a number of test cases defined in ANSI/ASHREA, Standard 140 (ANSI/ASHREA, 2007) and EN 15265 (CEN, 2007b) show that, although simplified calculation procedures are used, the precision of results is sufficient for use in the early design phases, see also *Section 4.2.4*. The latest version of the tool is accessible at http://www.vinduesvidensystem.dk/.

3.3 One-stop-shop for renovation

A study of the literature and a review of the state of the art showed that there is a need for a more integrated approach and a combination of far-reaching energy renovation measures if existing single-family houses are to be competitive with new buildings on the future housing market. A one-stop-shop model, where a single actor can offer a full-service package for renovation could provide the house owner with a holistic and long-term solution for a thorough energy renovation. Analysis of the few examples of such service models shows that they typically focus on applying a few of the available technical solutions and have not been successful in realizing large-scale energy efficiency gains (Tommerup et al., 2010, Vanhoutteghem et al., 2010). Based on these investigations, a method for renovating single-family houses is suggested in this thesis and also reported in Paper IV. The method is based on an ideal full-service concept and technical renovation packages targeted at two different types of single-family houses: master builder houses constructed before 1930 and standard detached houses constructed during the 1960s and 1970s. The package of technical solutions carried out during an overall or step wise planned renovation should be a good combination of the full range of technical solutions, especially if it is to achieve a low primary energy level. The calculation tool WinDesign (*Section 4.2*) was used to document energy use and thermal indoor environment. The cost-efficiency of the technical renovation packages was investigated using the criterion of Cost of Conserved Energy (CCE, see *Section 2.4.4*). To make the implementation of far-reaching energy-saving measures economically attractive to the house owner, the cost of these measures has been linked to normal renovation measures to avoid physical degradation, taking into account the ‘two-fold benefit’ of energy-saving renovation measures (Martinaitis, 2004, see *Section 4.3.3*). Another important aspect in the calculation of the cost-effectiveness of energy-saving measures is the lifetime of the investment. This is commonly set equal to the lifetime of the building component with the longest expected lifetime, i.e. the building structure. However, a major renovation combines several components that have different lifetimes and most building components have a shorter lifetime than the building structure, so for simplification purposes an average lifetime of 30 years has been taken into account in the cost calculations. This period corresponds to the normal loan period for real estate investments. Furthermore, a discount rate of 3% has been used.

4 Results

The results of the research work conducted to test the main hypothesis and four sub-hypotheses are presented in this chapter. Each paper appended to the thesis reports on the investigation of one of the sub-hypotheses. The main results in Papers I and II are presented in *Section 4.1*, which deals with the same topic/research objective. Results from Papers III and IV can be found in separate sections.

4.1 Window design in low-energy buildings

4.1.1 Windows and energy

Paper I investigated how space heating demand and thermal indoor environment are influenced by window size, type and orientation. More specifically, investigations were conducted for two window designs in a typical Danish single-family house: a traditional design with large south-oriented windows and smaller windows to the north; and a window design with an even window distribution where the glazing-to-floor ratio is the same for each room. The investigations also covered designs of the single-family house in accordance with the energy performance framework for current (Class 2010) and future buildings (low-energy Classes 2015 and 2020) in the Danish Building Code (see *Section 2.4.1*). To ensure a good thermal indoor environment, venting was set to 3 h^{-1} in all investigated scenarios, which corresponds to the maximum air flow rate possible for single-sided natural ventilation by automated opening of windows (Aggerholm and Grau, 2011). This requires special attention towards solutions for the opening of the windows when the home owners are not present, or at night. Besides venting, dynamically controlled external venetian blinds were initially used to prevent overheating. No other alternatives were considered as it has been demonstrated that these often do not provide enough protection against overheating (Janson, 2008, Larsen, 2011) and they reduce available daylight.

As mentioned, zone configurations were also considered to illustrate their importance in relation to the prediction of energy performance and thermal indoor environment and on the choice of window design. Details on the construction, layout of the building, and thermal zone configurations can be found in the appended paper. Initially, thermal indoor environment for each model with different thermal zone configurations has been evaluated as a weighed sum of hours above 26°C in each zone. However, to compare the thermal indoor environment of models with different thermal zone configurations, an additional evaluation of degree-hours with overheating in excess of 26°C was made. Space heating demand is evaluated as the annual energy needed for heating per square meter (kWh/m^2 per year) averaged for the whole house.

Orientation and window size

Using a 6-zone thermal model as a base case, Figure 2 shows results for space heating demand for the different orientations and glazing-to-floor ratios of the house constructed in accordance with the various energy performance requirements for the design with an even window distribution (scen1) and for a more traditional window design with large glazing areas to the south (scen2). In each case, dynamic solar shading was used on the southwest-facing façade.

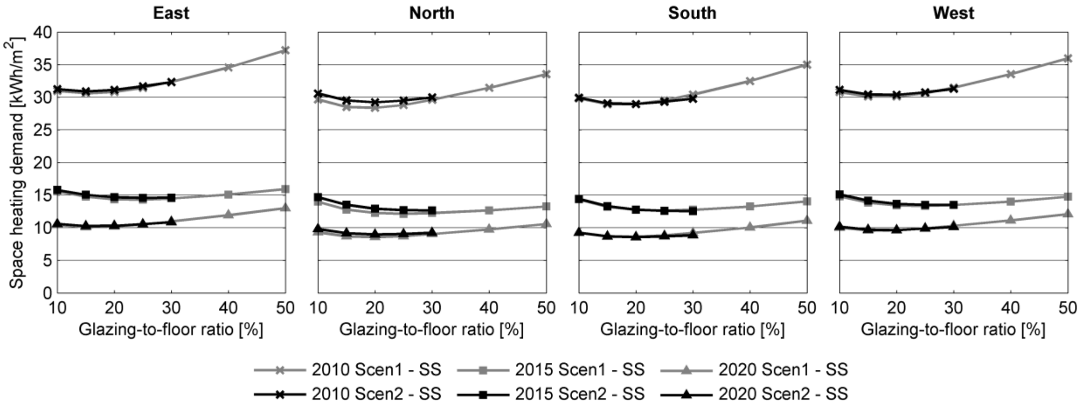

Figure 2: Space heating demand for different orientations and glazing-to-floor ratios.

In the traditional window design, the glazing area oriented towards the south accounts for 63% of the total glazing area. The rest of the glazing area is mainly oriented towards the north. If we consider the case with an even window distribution where the glazing-to-floor-ratio is equal in each room, the glazing area facing south is reduced by 14%, and the glazing area facing north is increased by 25%.

The results from comparison of the two window designs show that they perform similarly, so it can be concluded in accordance with findings from Persson et al. (2006) and Morrissey et al. (2011) that the effect of orientation and south-facing window size has decreased in the well-insulated homes of today and those that will be built in accordance with future energy performance requirements. In other words, the use of solar gains through south-oriented windows is not as important as is traditionally believed. This contrasts with current building design guidelines, which seek to take advantage of the free solar gains from large south-oriented windows. In fact, Figure 3 shows that increased solar gains through south-facing windows with enlarged glazing area do not result in additional reductions in space heating demand for the particular windows used in this study. However, the use of solar gains is still important to reduce space heating demand compared to north-facing rooms where space heating demand increases due to the increase in heat losses with larger glazing areas. This can also be seen in Figure 2, where optimal glazing-to-floor ratios of 20% can be found for the house when constructed in accordance with Class 2010 and Class 2020, and of 30% for the house constructed in accordance with Class 2015.

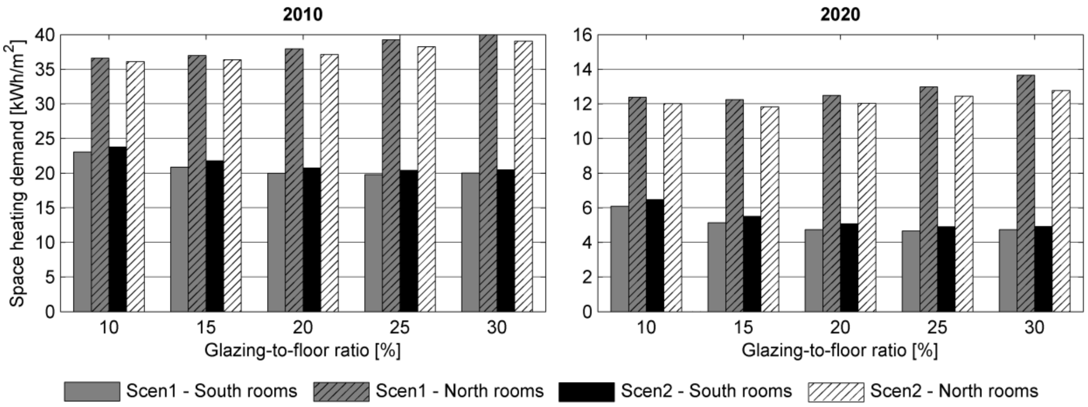

Figure 3: Comparison of space heating demand in north and south-facing rooms for different glazing-to-floor ratios with the south orientation of the house.

Apart from the optimal glazing-to-floor ratio, the increase in space heating demand is greater with increases in glazing area for the house constructed in accordance with Class 2010 than for the house constructed in accordance with Class 2015 or Class 2020. This can be explained by the larger heat losses in the less well-insulated building envelope with larger glazing areas, even though a window type with higher g-value was used as reference. As can be seen from Figure 4, this also results in more overheating. A more detailed investigation on the influence of U-value and g-value is presented in Paper II (see *Section 4.1.2*).

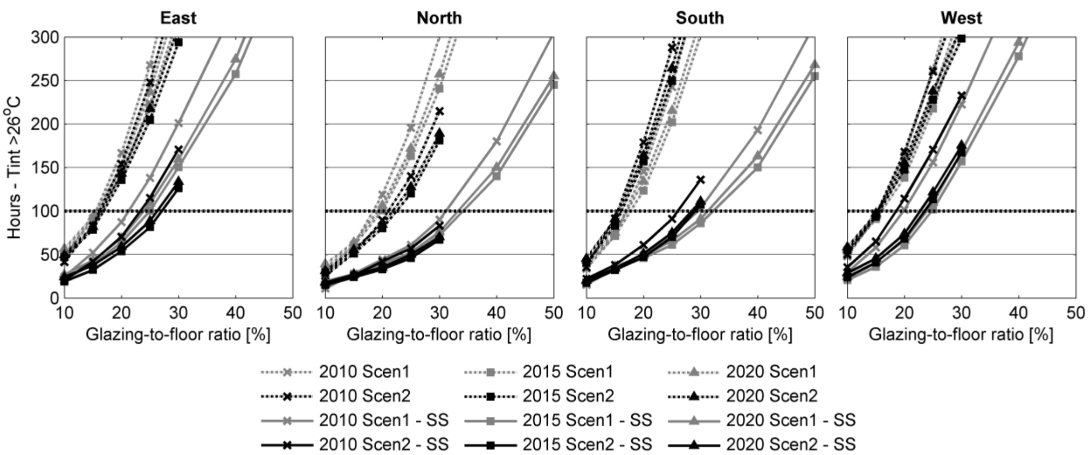

Figure 4: Hours with indoor temperatures > 26°C for different orientations and glazing-to-floor ratios and a scenario with and without dynamically controlled solar shading.

Maximum glazing-to-floor ratios from an overheating perspective in north- and south-oriented homes were identified that are slightly larger than the optimal glazing-to-floor ratios for space heating demand, see Figure 2. For the window design with an even window distribution, the maximum glazing-to-floor ratio from an overheating perspective was found to be 30% in north- and south-oriented homes. When a more traditional design is used, a maximum glazing-to-floor ratio of 25% is recommended in south-oriented homes. Otherwise, overheating with a traditional window design is almost at the same level as for a window design with an even distribution as long as good solar shading is used in combination with a high venting rate. In east- and west-oriented homes, the application of the dynamically controlled solar shading investigated on west-oriented windows was not as effective as on south-oriented windows. It is, however, reasonable to assume that the choice of a more suitable activation set point for the solar shading (shading is currently activated outside the heating season only when incident solar radiation on the windows exceeds 300W/m^2) would allow larger glazing-to-floor ratios.

As mentioned, optimal window sizes found from the perspective of space heating demand are generally smaller than those found from the overheating perspective, but differences in space heating demand for optimal window sizes and larger window sizes are very small, so it is up to the building owner to decide whether or not he wants larger window areas to allow for more daylight. Furthermore, because the orientation and size of windows is of less importance in well-insulated homes, windows can be positioned in the façade with considerable architectural freedom without sacrificing the indoor environment or causing a significant increase in the energy required for heating. This is also illustrated in Figure 5, where the difference in space heating demand for different variations in window distribution for an even window design is shown under the assumption that the indoor thermal environment is at the same level as in the original design with even window distribution. Table 4 illustrates the corresponding glazing-to-floor ratios for different orientations for the variations in window distribution.

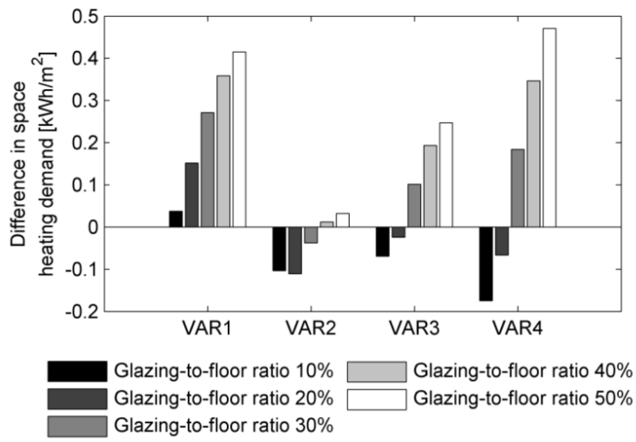

Figure 5: Differences in space heating demand for different variations in window distribution for an even window design.

Table 4: Glazing-to-floor ratios for different orientations for the variations in window distribution.

Glazing-to-floor ratio	Reference	VAR1	VAR2	VAR3	VAR4
North (%)	42.7	42.7	38.6	38.6	35.1
South (%)	54.0	46.2	46.2	42.9	42.7
East (%)	-	7.8	11.9	11.9	11.9
West (%)	3.3	3.3	3.3	6.6	10.3

However, an even distribution of the glazing-to-floor ratio is recommended, because this generally provides an improved thermal indoor environment in south-oriented rooms and will ensure a better daylight level, especially in north-oriented rooms. The aspect of daylight is investigated in more detail in Paper II.

Dynamic solar shading vs. permanent solar shading

Figure 2 showed that the use of dynamic solar shading on south/west façades allows for larger windows which provide improved views outside and better use of daylight when the shading is open. However, dynamic solar shading might not always be the best choice, see *Section 5.1.2*. As an alternative to dynamic solar shading, permanent solar shading in the form of glazing with solar-control coating was investigated in Paper I. Two different types of coatings were investigated for cases where solar-control coating was applied to both south- and north-oriented windows or only to south-oriented windows. Figure 6 gives results for the south orientation of the house constructed in accordance with Class 2010 and Class 2020, but similar trends were seen for the other orientations and with Class 2015.

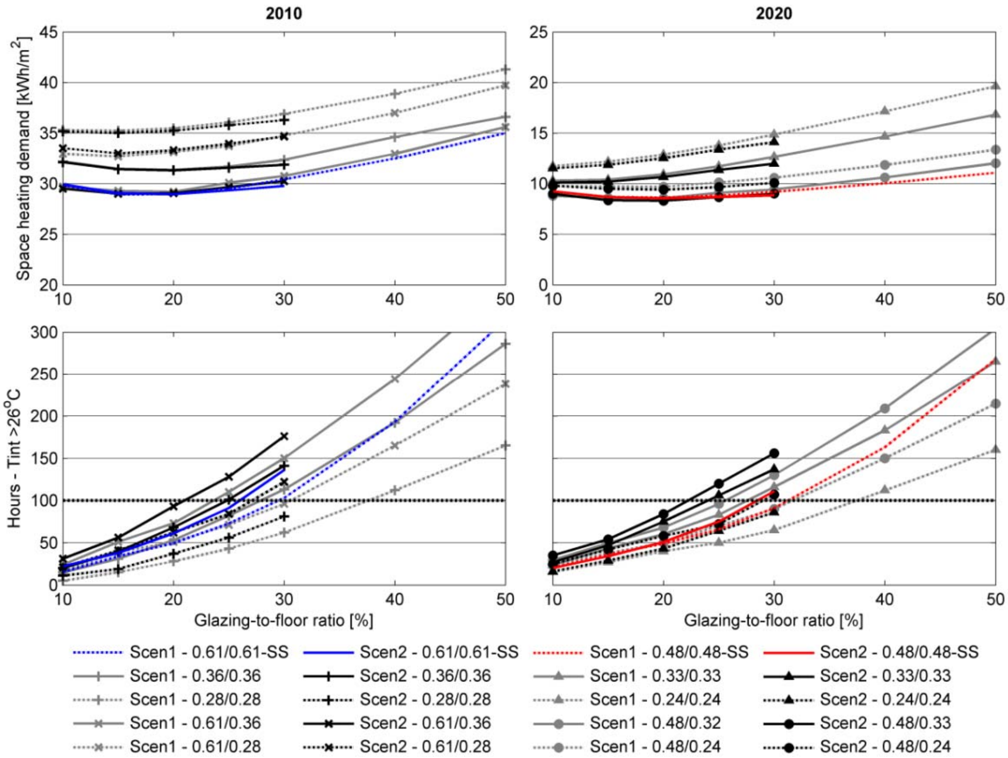

Figure 6: Space heating demand and hours with indoor temperatures > 26°C for different glazing types and glazing-to-floor ratios for the south orientation of the house.

The results show that the increase in space heating demand is small when glazing with solar-control coating is used only for south-oriented windows. Even if a more severe solar-control coating is used only for south-oriented windows, this still does not affect space heating demand very much, which indicates that there is a g-value above which the additional solar gains through south-oriented windows do not help reduce space heating demand. As a result, permanent solar shading based on application of glazing with solar-control coating on south-oriented windows could be used as a design alternative to dynamic solar shading. This was also validated by looking at peak heating demand, see Paper I. From the perspective of overheating, it was even found that for larger glazing-to-floor ratios, the use of glazing with solar-control coating is to be preferred over the use of dynamically controlled external shading for the particular case investigated.

Influence of thermal zone configurations

Figure 7 shows how thermal zone configuration can affect the prediction of space heating demand and overheating for a design with an even window distribution. Similar trends were observed for the traditional window design.

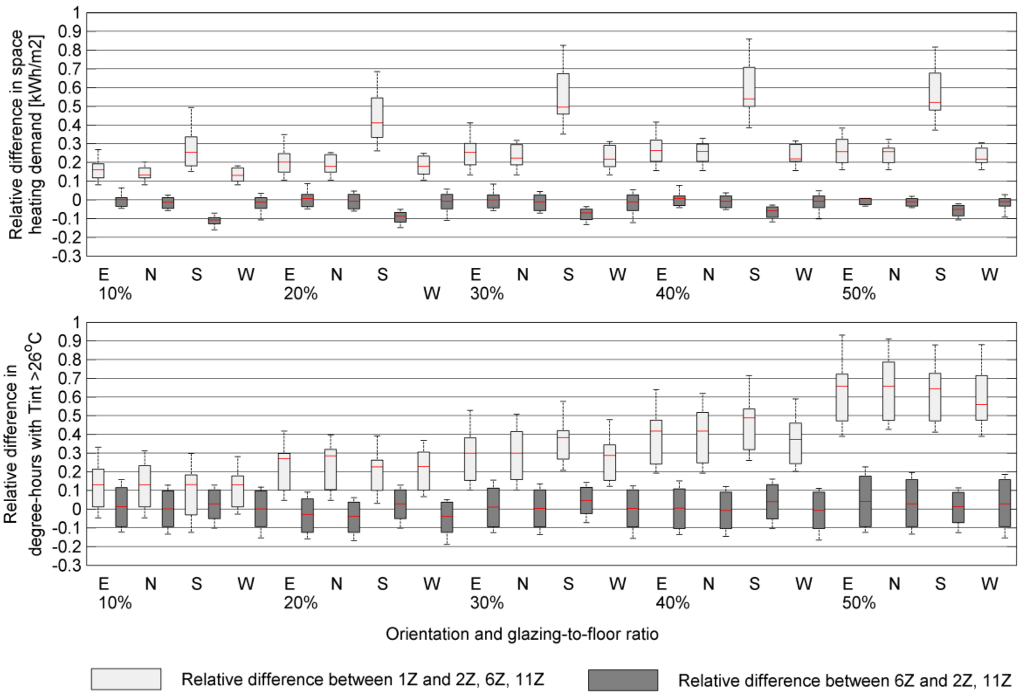

Figure 7: Comparison of space heating demand and hours with indoor temperatures > 26°C for different thermal zone configurations with different glazing-to-floor ratios and orientations.

The results show that using a single-zone model underestimates the energy needed for space heating and the risk of overheating because it assumes that air is well mixed in the house. In models with multiple thermal zones, space heating demand and overheating are seen more clearly because direct solar gains are isolated and thermal mass in the non-direct solar gain zones cannot be fully exploited. The underestimation in space heating demand is greatest for the south orientation, whereas the risk of overheating is underestimated for all orientations and increases with increase in glazing-to-floor ratio. With regard to thermal zone configuration, a difference between zones with direct and non-direct gains is needed. For better characterisation of space heating demand and the risk of overheating, however, it is recommended that models with more thermal zones should be used. However, this is a more time-consuming, but a more conservative approach: accuracy and influence on the prediction of space heating demand and overheating also need to be considered.

In addition to its influence on prediction of space heating demand and overheating, Paper I also shows that modelling a building using a single zone influences the choice of glazing-to-floor ratio and window design. Using a single-zone model, an optimal glazing-to-floor ratio could be found for the south orientation of the house that is 10% greater than the optimal glazing-to-floor ratio for both space heating demand and risk of overheating as found with other thermal zone configurations. Furthermore, using a single-zone model, differences between a design with an even window distribution and a traditional window design are also more pronounced than when using more thermal zones. Where the use of a single-zone model prefers the traditional design with large south-oriented windows, this is found less important with the other models.

For the comparison of different thermal zone configuration models in Paper I, the internal gains were assumed to be a constant of 5W/m2 for all thermal zones in each of the models, which is a figure often used in the early design phases in Danish single-family houses. Figure 8 shows a comparison with occupancy-data for residential buildings from EN ISO 13790 (CEN, 2008) which results in approximately the same average internal gains, just distributed differently, see Table 5.

Table 5: Internal gains from occupants and appliances [W/m²].

	Weekdays		Weekends	
	Living room and kitchen	Other conditioned areas (e.g. bedrooms)	Living room and kitchen	Other conditioned areas (e.g. bedrooms)
0h-7h	2	6	2	6
7h-17h	8	1	8	2
17h-23h	20	1	20	4
23h-24h	2	6	2	6

As expected, the influence of thermal zoning on space heating demand is greater when different internal gains in rooms are taken into account and it becomes more important to consider models with multiple thermal zones for prediction of space heating demand. However, the influence of orientation on space heating demand then also increases. With regards to thermal indoor environment, only small differences can be seen on whole building level, except for when each room in the house is modelled as a thermal zone for the traditional window design.

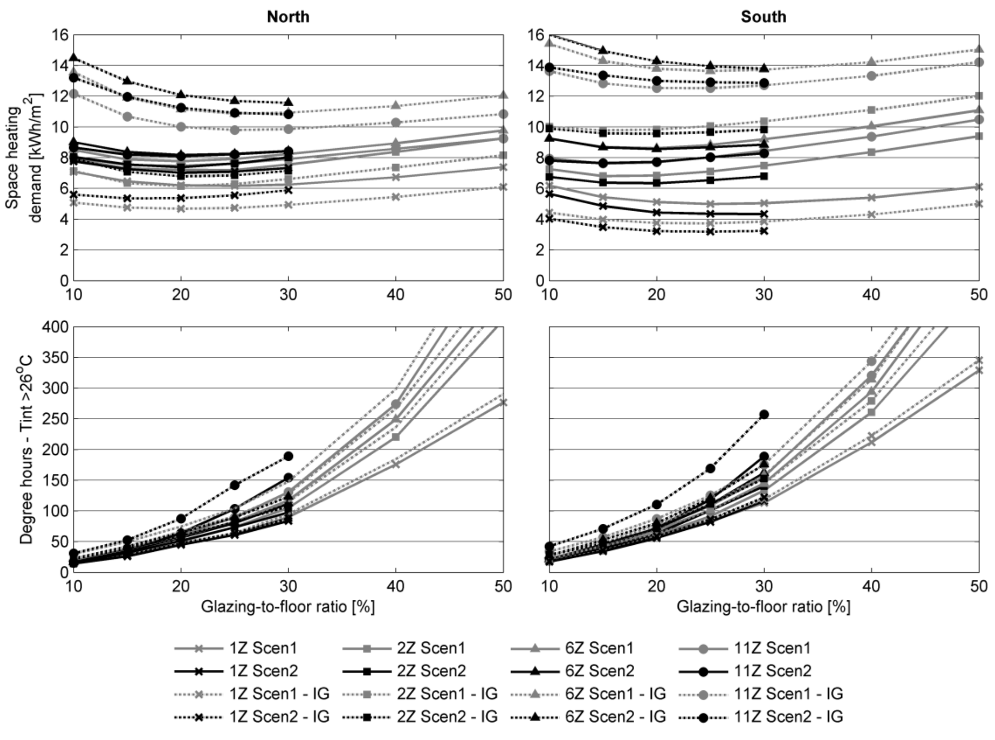

Figure 8: Comparison of space heating demand and degree hours with indoor temperatures > 26°C for different thermal zone configurations and internal gains with different glazing-to-floor ratios and orientations for the house constructed in accordance with 2020 energy performance requirements.

4.1.2 Windows and daylight

The aim of the research described in Paper II was to investigate in more detail the link between various window design parameters and their combined effect on energy consumption, daylight availability and thermal indoor environment. More specifically, the aim was to investigate the relationship between glazing-to-floor ratio, orientation, glazing U-value, g-value and light transmittance for various room geometries representing Danish ‘nearly zero-energy’ houses.

Since the tradition for mechanical space cooling is limited in Denmark due to the climate, the evaluation of energy consumption was based on space heating demand alone, while thermal comfort was considered a boundary condition restricting the allowable space of window solutions. Thermal comfort was evaluated on basis of the Danish building code requirements for nearly-zero residential buildings, see *Section 2.4.2*. Daylight was evaluated as an independent performance parameter, rather than expressed in terms of a reduction in energy used for artificial lighting. The target and methodology for the evaluation of daylight availability was selected with reference to the on-going discussion about how European daylight standards can be upgraded in a way that approaches climate-based daylight modelling (CBDM). A climate-dependent target daylight factor (DF_{target}) was used for the evaluation of available daylight based on the target for median illuminance indoors (E_{target}) and the diffuse median illuminance available outdoors ($E_{median\ diffuse}$):

$$DF_{target} = \frac{E_{target}}{E_{median\ diffuse}} \qquad (1)$$

The diffuse median illuminance available outdoors was calculated as the cumulative availability of diffuse illuminance during daylight hours. When E_{target} is set to 300 lux, which is considered adequate by most building users (Mardaljevic and Christoffersen, 2013), the target daylight factor in Copenhagen is calculated to be 2.11% (Mardaljevic and Christoffersen, 2013). In this research, the final daylight access of the various room geometries was evaluated as the achievement of 300 lux (or DF_{target} 2.11%) across 50% of the work plane. Since the median of the outdoor diffuse illuminance ($E_{median\ diffuse}$) is used for the calculation of this achievement, this means that, for half of the daylight hours in a year, half of the surface of the horizontal work plane receives 300 lux or more daylight. One should, however, keep in mind that using this approach for the evaluation of available daylight is not a fully climate-based approach and cannot be used as a measure for equal daylight availability for south- and north-oriented rooms over time under realistic sky conditions. Therefore, a comparison with additional results from annual calculations using realistic sun and sky conditions for the location of Copenhagen is also included in this thesis (as is a comparison with results using the normal daylight factor as well). For a more detailed description of the daylight metric used for the evaluation of daylight, see Paper II.

To obtain useful information about the relationship between the various window design parameters and their effect on space heating demand, the thermal indoor environment and daylight, the results for each of these are presented in the same graphical illustration.

For each room geometry investigated, space heating demand was plotted in a contour plot as a function of the glazing-to-floor ratios and g-values for north and south orientations separately. The combinations of glazing-to-floor ratio and g-value at which indoor temperatures were above 26°C for more than 100 hours were plotted as the boundary indicating overheating on the contour plot, see Figure 9.

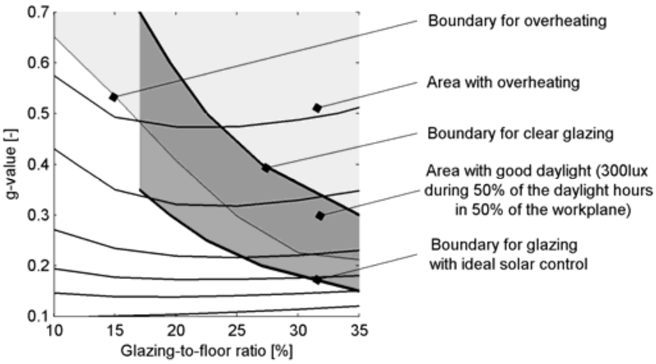

Figure 9: Conceptual illustration of a contour plot of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target.

The boundary for daylight at different combinations of glazing-to-floor ratio and g-value was established through the relationship between g-value and light transmittance, i.e. the ‘daylighting efficiency’ of the glazing. Two boundaries for daylighting were used, one for glazing with ideal solar control (maximum daylight efficiency 2) serving as the lower limit, and the other for clear glazing (daylight efficiency 1) representing the upper limit for daylight availability. The space of solutions defined by the boundaries for daylight and thermal indoor environment can then be used to find a window design with the lowest space heating demand.

Effect of U-value, g-value and glazing-to-floor ratio

Before discussing the full space of solutions defined by the targets for daylight and the thermal indoor environment, findings from a more detailed investigation into the interrelationship between the glazing U-value, g-value and glazing-to-floor ratio in Paper II and their effect on space heating demand and overheating are discussed. Results illustrated for the whole space of solutions for a room with dimensions of 4m by 4m in Figure 10 show that variations in U-value have only marginal effect on the thermal environment for the range of variables considered. On the other hand, space heating demand and the choice of glazing-to-floor ratio and g-value to reduce space heating demand are to a high degree determined by the glazing U-value. In this connection, the orientation of the rooms is also important. In south-oriented rooms, it was found (see also Paper I) that from the perspective of space heating demand there is an upper limit for the amount of solar gain that can be utilised efficiently. The ability to utilise solar gains varies across U-values, but for U-values of 0.5 W/m^{2}K and below a relatively pronounced stagnation can be observed at g-values as low as 0.3–0.4. In north-oriented rooms, where space heating demand is higher, the benefits of high g-values for reducing space heating demand decrease with lower U-values and with higher g-values, but in general the importance of a high g-value remains significant for the whole range of variables investigated.

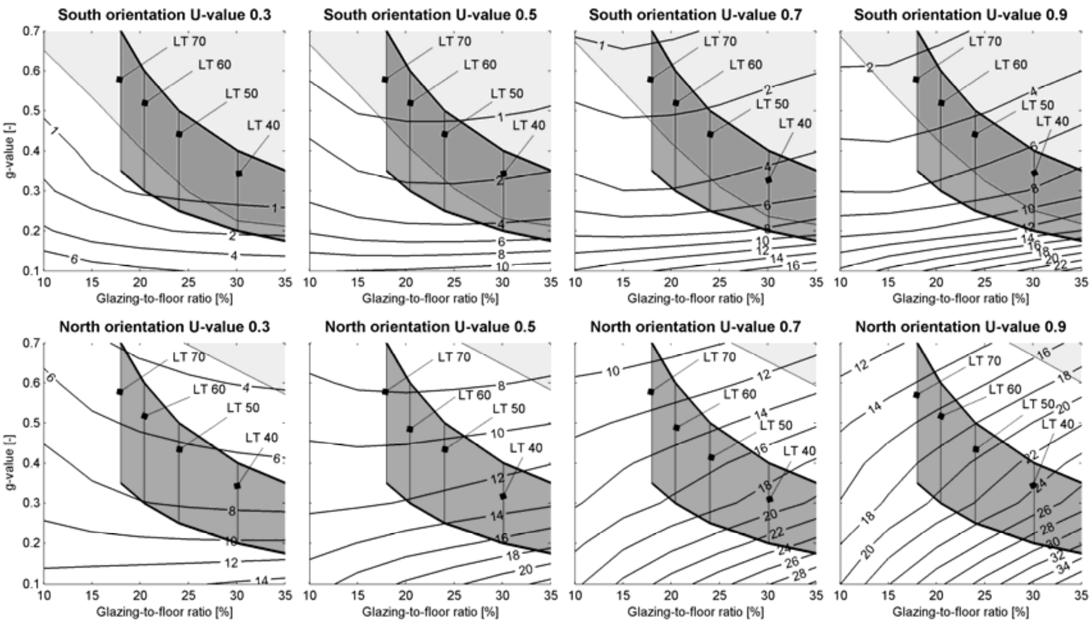

Figure 10: *Contour plots of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for a room with dimensions of 4m x 4m and for various glazing U-values.*

The effect of the glazing-to-floor ratio on space heating demand also depends on the glazing U-value. An optimum glazing-to-floor ratio of approximately 15–20% can be found for all room geometries in south-oriented rooms. For high glazing U-values, larger glazing-to-floor ratios result in an increase in space heating demand, while for glazing U-values below 0.5 W/m^{2}K large glazing-to-floor ratios can be chosen freely. This indicates that the amount of solar gain that can be utilised in well-insulated buildings can only outweigh the additional heat losses that occur with larger glazing-to-floor ratios when low U-values are used.

Similar tendencies can be found for the lower U-values in north-oriented rooms. It should be noted though that, when considering the U-value of 0.3 W/m^{2}K, it can actually be seen that while the positive effect of increased glazing-to-floor ratio on the reduction of space heating demand stagnates significantly in south-oriented rooms due to the limited amount of solar gain that can be utilised, the positive effect of increased glazing-to-floor ratios remains relatively pronounced in north-oriented rooms. Furthermore, for high U-values, the negative effect on space heating demand of using very large-glazing-to-floor ratios is less pronounced in north-oriented rooms than in south-oriented rooms, because high g-values can be used in north-oriented rooms irrespective of glazing-to-floor ratio since very little overheating occurs. In south-oriented rooms, however, the prevention of overheating will determine the final selection of g-value for the various glazing-to-floor ratios, irrespective of glazing U-value.

Daylight achievement and the space of solutions for different geometries

General findings with regard to the space of solutions and daylight achievement in the room geometries investigated in Paper II are reported here. For example, Figure 11 illustrates the space of solutions for two different room geometries with width-to-depth ratios of 1:1.5 and 1.5:1 for a glazing U-value of 0.5 W/m^{2}K.

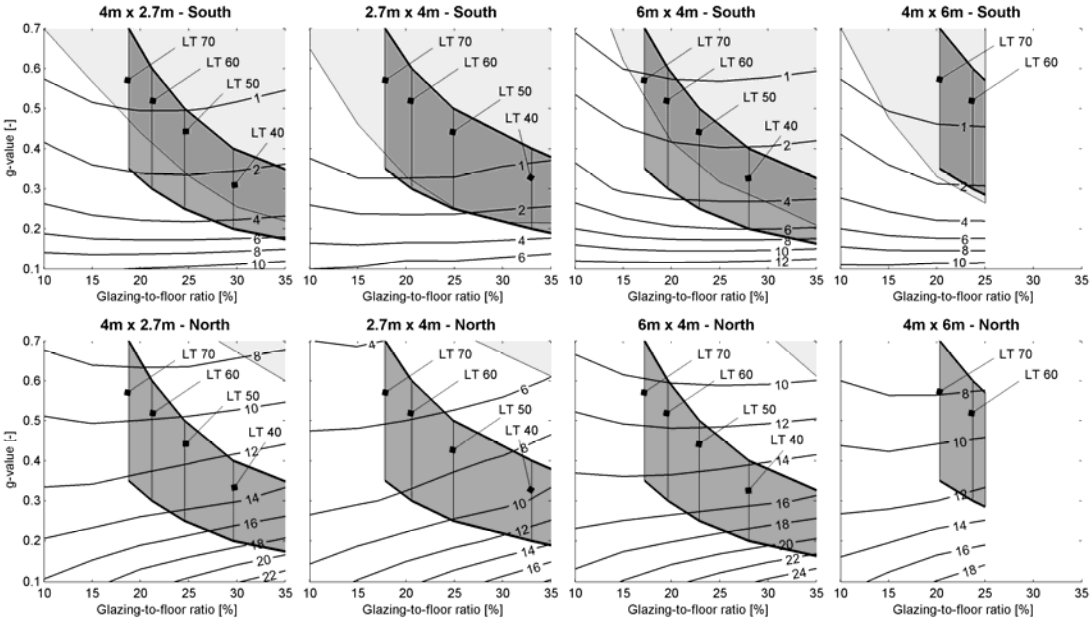

Figure 11: Contour plots of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for two different room geometries with a width-to-depth ratio of 1:1.5 and 1.5:1 and for a glazing U-value of 0.5 W/m2K.

As Figure 10 and Figure 11 show, the space of solutions for which both thermal comfort and daylight conditions are satisfactory is considerably larger for north-oriented rooms than for south-oriented rooms. Furthermore, comparison of results for the different geometries in Paper II shows that where small deep geometries are preferable from the perspective of space heating demand in both north- and south-oriented rooms, wide rooms with a shallow depth are preferable from the point of view of daylight. To achieve the same daylight access in deep rooms as in wide rooms with the same floor area, a larger glazing-to-floor ratio is needed. This will result in an increase in space heating demand, especially when high U-values are used, which could outweigh some of the benefits of deep rooms in terms of energy consumption.

With regard to room geometry, it was also found that, in deep or very narrow south-oriented rooms, either the daylight conditions or the thermal comfort must be compromised when a window design is chosen. And to achieve the daylight target without overheating in other room geometries, windows must be carefully dimensioned on the basis of the daylight target, and solar-coated products with close to ideal daylight efficiency must be used, see Figure 12. For north-oriented rooms, none of the geometries experience problems with overheating before achieving the daylight target, even when clear glazings are used. However, in deep rooms facing north, the target for daylight cannot be met due to the physical limitations of the geometry.

When considering the geometries that can achieve the daylight target without overheating, Figure 12 shows that glazing-to-floor ratios of approximately 17–25% are needed to achieve the specified daylight target for light transmittances of 0.7–0.5 in both north- and south-oriented rooms when the daylight availability for both orientations is evaluated under a CIE overcast sky. Within this range, of course, a slight variation in the glazing-to-floor ratio needed to achieve the daylight target is seen across the different geometries.

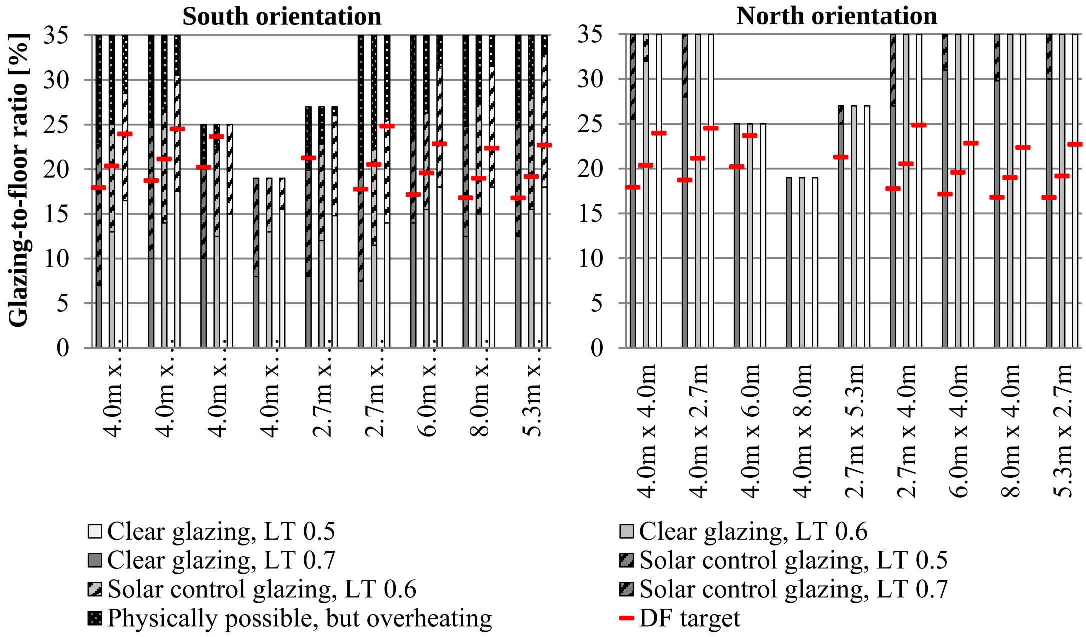

Figure 12: Indication of glazing-to-floor ratios and glazing types that can be used to achieve the daylight target (DF target) without overheating for light transmittances of 0.7, 0.6 and 0.5 for various room geometries.

Figure 12 also shows that in deep and narrow rooms, the daylight target can only be achieved for light transmittances of at least 0.6-0.7, but in general glazing products ranging from high to low light transmittance can be used if they are combined with the right glazing-to-floor ratio. However, glazing types with high light transmittances and as high g-values as possible generally allow for a lower heating demand than products with lower light transmittances and as high g-values as possible.

For south-oriented rooms, it was found that, for high light transmittances, the range of available g-values is slightly larger than for low transmittances and that glazing products with low U-values and high light transmittances generally provide a better fit between the maximum allowable g-values from the perspective of overheating and the g-values at which the effect on space heating demand starts to stagnate. Furthermore, a high light transmittance will allow the use of smaller glazing-to-floor ratios (within the range of 17-25%), which could be an advantage in cases where less glazing is desirable due to cost and will also allow for the lowest possible space heating demand for high U-values. In north-oriented rooms, the use of small glazing-to-floor ratios and high light transmittances is also preferable when using higher glazing U-values. When using low glazing U-values, larger glazing-to-floor ratios with lower light transmittance could be used, provided that clear glazings with high g-values are used to reduce space heating demand. As mentioned, high g-values can be used irrespective of the glazing-to-floor ratio, because the risk of overheating is limited in north-oriented rooms. However, the maximum achievable g-values that can be used depend on technical considerations that are especially important to take into account when considering the lowest U-values.

Spatial distribution of daylight

The available daylight was evaluated on basis of the requirement that 300 lux should be met during 50% of the light hours in 50% of the working plane. This provides some information about the spatial distribution of daylight in a room that using an average daylight factor, for example, would not provide. Furthermore, the use of an average daylight factor could result in an overestimation of daylight. On the other hand, it can sometimes be useful, because it also takes into account daylight in corners. In the following, the spatial distribution of daylight for the various room geometries is further investigated to see whether the target for daylight can also provide enough daylight at the back of the room. Figure 13 illustrates the daylight profile along the middle of a room with dimensions of 4m by 4m when the target for daylight is reached (see also Figure 12 for glazing-to-floor ratios).

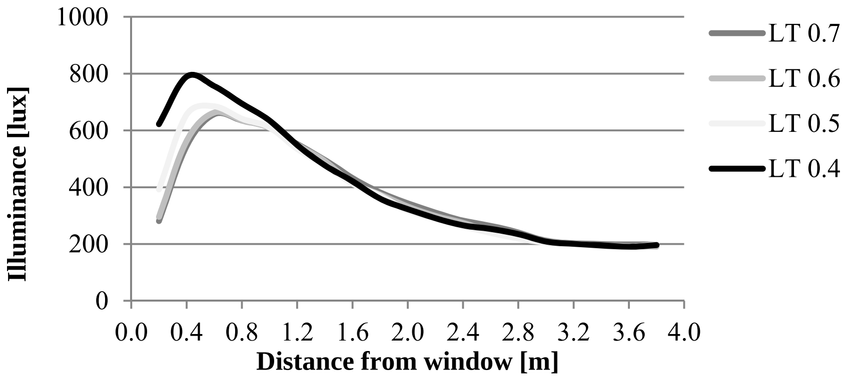

Figure 13: Daylight profile in the middle of a room with dimensions of 4m by 4m.

As Figure 13 shows, the illuminance in the middle of the room is slightly greater than the target illuminance of 300lux considered adequate by most building users. Recent research has also shown that a point can be considered ‘day-lit’ if its illuminance reaches 300 lux for at least 50% of the daylight hours (Reinhart and Weissman, 2012). Near the back wall of the room, the illuminance levels for the different light transmittances approach 200lux. According to the Danish standard DS700, this is adequate in the immediate surroundings of workplaces, whereas 100lux is seen the minimum for performing work under daylight conditions (DS, 2005).

For residential buildings designed in accordance with the energy framework ‘Class 2020’, the Danish Building Code (DEA, 2013) states that a minimum glazing-to-floor ratio of 15% is needed for primary rooms to be ‘day-lit’. A recent addition in the building code states that, as an alternative, daylight in primary rooms can be assumed sufficient when a daylight factor of 2% can be reached in 50% of the room (DEA, 2013). Figure 14 and Figure 15 illustrate results from evaluating the daylight factor in the middle of the room and near the back wall for the various geometries when the target for daylight has been reached.

The daylight factor was evaluated by using two different values for the outdoor illuminance: first, median DF, based a diffuse median illuminance available outdoors of approximately 14,000lux (based on calculating the cumulative availability of diffuse illuminance during the daylight hours from the climate file for Copenhagen), and second, standard DF, using an outdoor illuminance where the CIE overcast standard sky corresponds to 10,000lux.

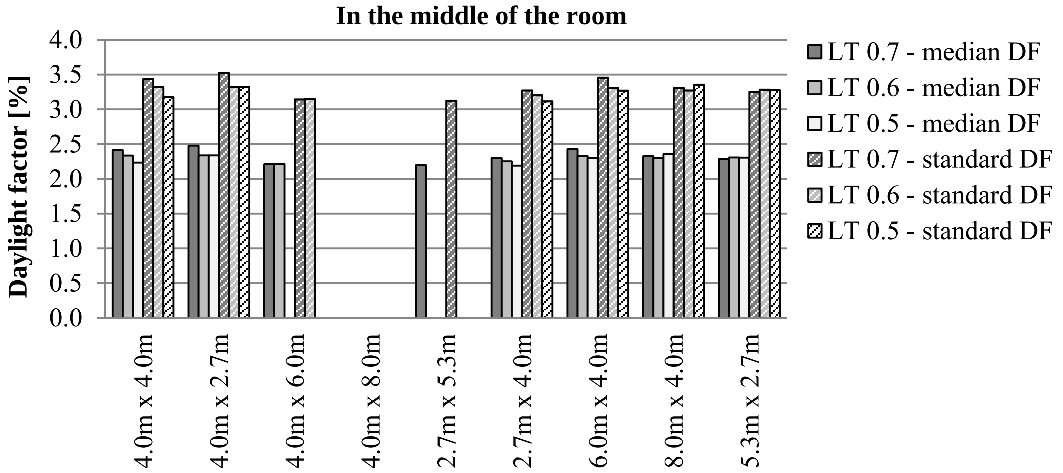

Figure 14: Comparison of median daylight factor (median DF) and daylight at 10,000lux (standard DF) for the various room geometries and light transmittances in the middle of the rooms.

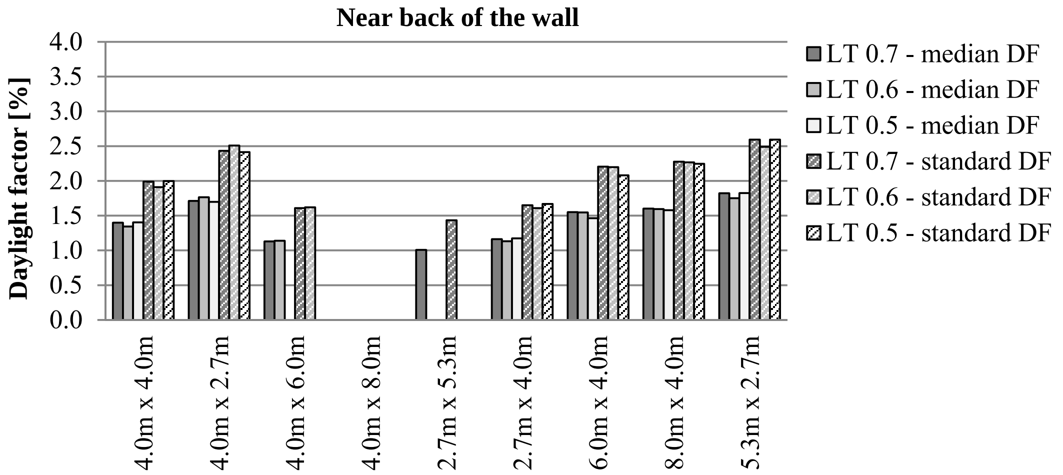

Figure 15: Comparison of median daylight factor (median DF) and daylight at 10,000lux (standard DF) for the various room geometries and light transmittances near the back wall of the rooms.

Figure 15 shows that using a target for daylighting of 300lux in 50% of the light hours in 50% of the work plane, a median daylight factor of between 2 and 2.5% in the middle of the room can be achieved depending on the light transmittance for all geometries able to achieve the daylight target. This corresponds quite well with the alternative requirement for a daylight factor of 2% across 50% of the room stated in the Danish Building Code. However, usually calculations of daylight factor are performed at the time when the outdoor illuminance of the CIE overcast standard sky corresponds to 10,000lux, where daylight factors between 3 and 3.5% can be found. Since no realistic sun and sky conditions are taken into account, one could argue that the requirements in the Danish Building Code should be made more ambitious to ensure a good daylight level.

Near the back wall of the rooms, daylight factors in the range of 1–1.8% and 1.9–2.5% can be found using the median daylight factor and the standard daylight factor, respectively. Additional results from the evaluation of daylight factors in the back corners of the various room geometries also revealed that the daylight factor is never less than 1% (using median DF) and 1.4% (using standard DF) in the corners of rooms where the daylight target is achievable. This indicates a good distribution of daylight without corners that are too dark (Johnsen and Christoffersen, 2008.

Comparison with results from CBDM

In the previous section, daylight was evaluated using a climate-dependent daylight factor which provides a transition between the current practice of using the standard daylight factor method and the use of CBDM (Mardaljevic and Christoffersen, 2013). However, this approach does not take into account the effect of orientation. As a result, glazing-to-floor ratios for providing enough daylight were found to be the same for both north and south-oriented rooms. This is an improvement in comparison with common design practice where large south-oriented and small north-oriented windows are used for the design of well-insulated houses. The use of an even window distribution will provide a generally better daylight distribution in houses and the chance of a better thermal indoor environment at no extra cost in space heating demand, see also the findings in previous section.

With regard to room geometry, it was found that wide rooms are preferable to deep rooms in both north and south-oriented rooms from the point of view of providing enough daylight. However, in traditionally designed houses, south-oriented rooms are often made deeper than north-oriented rooms because south-oriented rooms also have access to direct sunlight. Hence, it is interesting to compare results from using the climate-dependent daylight metric with results from climate-based modelling of daylight availability in rooms with various geometries and orientations.

One commonly-used climate-based metric is daylight autonomy (DA), which describes the percentage of hours during which a minimum work plane illuminance threshold is reached by daylight alone (Reinhart and Walkenhorst, 2001). To make it possible to compare results from CBDM with the results based on the use of the climate-dependent metric, daylight availability was evaluated as the achievement of a daylight autonomy of 50% at a threshold of 300lux. This achievement was targeted at 50% and 100% of the work plane. For simulations of daylight availability, hourly mean values were used in accordance with the hourly resolution of available weather data (Jensen and Lund, 1995). When it comes to the evaluation of electrical lighting consumption, this is a simplification that could neglect short-term dynamics and introduce errors in control strategies and the prediction of electricity demand (Walkenhorst et al., 2002, Roisin et al., 2008, Iversen et al., 2013). However, since no electrical lighting consumption was included, this simplification was considered accurate enough.

Figure 16 compares the glazing-to-floor ratios and glazing types needed to achieve the daylight target using the climate-dependent metric with those needed when using a climate-based metric. Comparison of results obtained by using the standard daylight factor approach with results from a climate-based approach usually show that the daylight factor approach underestimates the daylight levels in south-oriented rooms and overestimates them in north-oriented rooms (Mardaljevic, 2000). Results in Figure 16 show, however, that daylight availability is underestimated in both north and south-oriented rooms when using the climate-dependent daylight factor.

For south-oriented rooms, it can be seen that the DA target set to cover 100% of the work plane approximates the climate-dependent daylight factor in 50% of the work plane (DF target). In north-oriented rooms, results from evaluation of daylight based on the climate-dependent daylight factor are found between the DA for 50% and 100% coverage of the work plane.

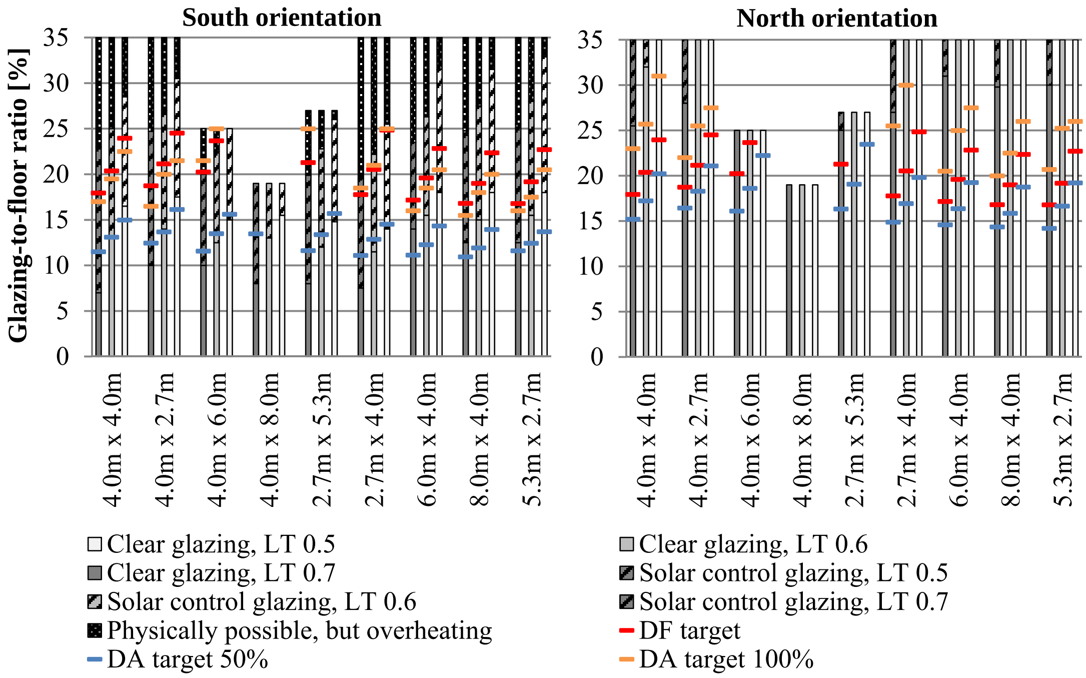

Figure 16: Comparison of glazing-to-floor ratios and glazing types that can be used to achieve the daylight target based on evaluation of a climate-dependent metric (DF target) and a climate-based metric (DA target) without overheating for light transmittances of 0.7, 0.6 and 0.5 for various room geometries.

To achieve a DA target across 50% of the work plane in south-oriented rooms, a glazing-to-floor ratio of 11-16% is needed at different light-transmittances. Glazing with solar control is then needed to avoid overheating in deep rooms. However, in wide rooms, clear glazing, which results in lower space heating demand, could be used to achieve the DA target in 50% of the work plane. In north-oriented rooms, a glazing-to-floor ratio of 15-20%, and in deep rooms up to 24%, is needed to achieve the DA target across 50% of the work plane. This corresponds well with the optimal glazing-to-floor ratios found from the perspective of space heating demand. In south-oriented rooms, however, the glazing-to-floor ratios are smaller than optimal from the perspective of space heating demand.

All the various room geometries (except for the room with dimensions of 8m by 4m) can reach a DA target of 50% in the work plane without resulting in overheating in both north and south-oriented rooms. This is in contrast with evaluations based on the climate-dependent daylight factor, where it was found that in deep or very narrow rooms either the daylight conditions (in both north and south-oriented rooms) or the thermal comfort (in south-oriented rooms) must be compromised when a window design is chosen. In other words, using CBDM to evaluate a DA target set to 50% of the work plane allows greater freedom of choice with regard to room geometry. However, when the DA target is set to cover 100% of the work plane, wide rooms are preferable.

It seems that the choice of daylight target is rather open because each has its advantages and disadvantages. In south-oriented rooms, the glazing-to-floor ratios to reach a DA target across 50% of the work plane are smaller than optimal from the perspective of space heating demand. However, it is possible to dimension south-oriented rooms for high daylight quality by using larger glazing-to-floor ratios because overheating can be reduced by using solar control glazing. Furthermore, Figure 17 shows there is very little variation in the difference in space heating demand when larger glazing-to-floor ratios are used to obtain more daylight, especially with low glazing U-values. Figure 17 also shows that in north-oriented rooms, the use of glazing with a low U-value actually helps reduce space heating demand when larger glazing-to-floor ratios are used to achieve a more ambitious daylight target (i.e. 100% coverage). However, when higher glazing U-values are used, using a climate-dependent target is a good compromise if we do not need the same amount of daylight in north and south-oriented rooms. This is further reflected upon in *Section 5.1.3*.

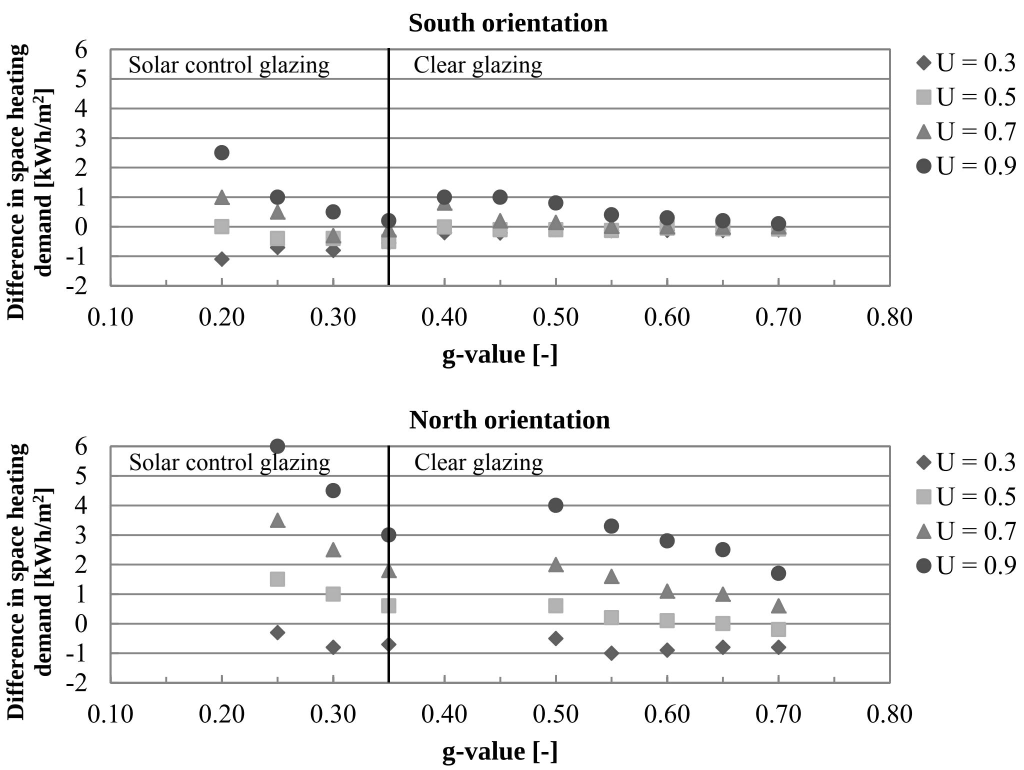

Figure 17: Illustration of the difference in space heating demand between a DA target for 50% and 100% coverage of the work plane for a room with dimensions of 4m by 4m.

4.1.3 Recommendations and guidelines

We can conclude from the work described in previous sections that, in well-insulated Danish single-family houses, the choice of window size and orientation is no longer a big issue from the perspective of heating demand as long as low glazing U-values are used. However, careful attention should be given to avoid overheating in south-oriented rooms by using dynamically controlled solar shading or glazing with solar-control coating, which can very well be used as a cheaper alternative to the use of dynamically controlled solar shading.

The research showed that windows can be designed on a room by room basis to achieve both an optimal daylight level in all rooms and a good thermal indoor environment. The work described in Paper II was an example of an approach by which window solutions with minimum space heating demand can be chosen within a space of solutions for a room with a certain geometry defined by targets for minimum daylight availability and overheating through the use of charts. However, this requires extensive parameter analysis. Another strategy to obtain an optimal window design for Danish single-family, 'nearly zero-energy' houses could be as follows:

1 Determine the minimum window size in all rooms with regard to daylight

As a starting point, use an even window distribution in all rooms, i.e. use the same glazing-to-floor ratio in all rooms for all orientations. Generally, a minimum glazing-to-floor ratio of 17-25% of the internal floor area is required in all rooms to obtain a daylight factor of 3% in 50% of the area with light transmittances of 0.7-0.5. In the case of corner rooms, the glazing-to-floor ratio could be divided between the two façades of the corner room, relative to the length of each façade of the corner room.

Depending on room width and depth and the useful area of the room, the minimum glazing-to-floor ratio might be adjusted. Avoid designing very narrow rooms or rooms with depths greater than twice the floor-to-ceiling height. In addition to room width and depth, orientation, overhang, window width, and window height also influence the choice of minimum window size with regard to daylight in the different rooms of a home (Vanhoutteghem and Svendsen, 2011). For optimal daylight access at the back of the room, it is recommended that the windows should be as high as possible in the façade. With regard to orientation, if the same daylight level is required in both north- and south-oriented rooms, climate-based daylight modelling should be used.

Other factors that influence the choice of sizes with regard to daylight are factors such as surface colours in the room, wall thickness and window reveal (Szameitat and Svendsen, 2011).

2 Calculate the maximum window size in each room with regard to overheating

To quantify the risk of overheating, a dynamic simulation tool should be used to determine hourly values for indoor air temperatures. For good characterisation of the risk of overheating, it is recommended that the thermal model of the building is divided into thermal zones distinguishing between zones with direct and non-direct access to solar gains.

When the hourly values for the indoor air temperatures exceed a certain comfort temperature, there is a risk of overheating. While this is crucial in the primary rooms of a home (e.g. living room, kitchen and workspace), this might not be so much of a problem in secondary rooms (e.g. storage room, master bedroom).

The thermal model should contain input data about ventilation rate, venting rate, thermal mass, glazing type and any use of solar control, because these factors will play an important role for the determination of maximum window sizes with regard to overheating. To reduce the risk of overheating, a minimum venting rate of $3h^{-1}$ is recommended. As for solar control, in south-oriented rooms where there is a requirement for large glazing-to-floor ratios, glazings with solar-control coating and g-values below 0.3, but with a light transmittance as high as possible, can be used as a cheaper alternative to the use of dynamically controlled solar shading. In north-oriented rooms, glazing types can be chosen with little risk of overheating. However, clear glazings with high g-values are recommended to reduce space heating demand.

3 Calculate energy consumption for the different window sizes

Simulations should be performed in a dynamic simulation tool. It is beneficial if the same simulation tool and thermal model can be used for documentation of the thermal indoor environment and energy consumption. Furthermore, it should be easy to perform parameter analysis of different window design solutions.

4 Choose a window size for each of the rooms based on results in previous steps

However, try to use uniform window sizes where possible in the overall design. In the choice of window size and design, not only energy consumption, but also cost should be considered.

5 Document the energy consumption and indoor environment for the final window design.

4.2 WinDesign: a simplified calculation tool (for the evaluation of windows in residential buildings)

As mentioned in *Section 3.2*, the tool WinDesign was originally developed to help engineers and architects with the selection of windows in the early design phases. This chapter describes in more detail the workflow and the basis for the calculation procedures in the various steps in the tool. Further information can be found in Paper III and a report by Asmussen (2009). Coupling of the tool with ArchiCAD, application of the tool and results from validation of the tool are also briefly discussed.

4.2.1 Workflow and calculation procedures

WinDesign is organized in four different steps, each corresponding to a specific analysis. The idea is that the different steps gradually increase in level of detail and support the design decisions throughout the design process. In each step, a number of different scenarios can be defined where it is possible to vary certain parameters. Based on the results from the four steps, the various scenarios can be compared and the most appropriate window design with regard to energy consumption, thermal indoor environment, daylight (based on electricity consumption for artificial lighting), and cost can be selected, see Figure 18.

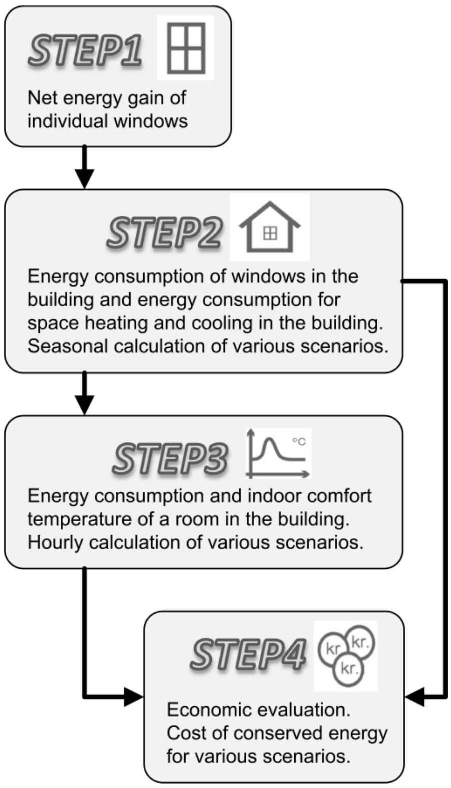

Figure 18: Flowchart of the calculations performed in the different steps in WinDesign.

Each step has its own calculation module and user interface developed to facilitate the workflow suggested in Figure 18. In the following, the four steps are briefly described.

Step 1: Net energy gain of individual windows

In Step 1, the general energy performance of a wide range of individual windows is evaluated based on the concept of Net Energy Gain (NEG). In order to do so, the user can create various windows based on knowledge of configuration, size and components (glazing, frame/sash, mullions/transoms and glazing bars). Window components can be selected from a database, but it is also possible to define new components in the database. The Net Energy Gain (NEG, kWh/m^2) for each window is calculated according to the definition by Nielsen et al. (2000) for single-family houses (see also *Section 2.2.3*). The solar radiation I (kWh/m^2), and the degree – hour D (kKh) for the given heating season are automatically calculated based on the available weather data. The weather data required for calculations in WinDesign consists of hourly values for external temperature (°C), direct normal solar radiation (W/m^2), horizontal diffuse solar irradiation (W/m^2), and global horizontal solar illuminance (lx). These values can be extracted in WinDesign from standard weather data found in the IWEC-data format (International Weather data for Energy and Climate simulations, IWEC, 2013). However, for Denmark, calculations are performed by using weather data for the Design Reference Year (DRY, Jensen and Lund, 1995).

After calculation of the NEG, the best-performing windows can be selected and used in the further analysis. When design of Danish residential buildings is considered, the user should keep in mind the requirements for minimum NEG as defined in the Danish Building Code, see *Section 2.4.1*.

Step 2: Energy performance of windows in the dwelling

The aim of Step 2 is to calculate the energy consumption of the windows in a specific building and to document the building´s energy consumption for space heating and cooling. The calculations are performed in accordance with the seasonal method described in the European standard EN ISO 13790 (CEN, 2008). This method is a quasi-steady-state method based on a seasonal balance of heat losses (transmission and ventilation) and heat gains (solar and internal). Dynamic effects that give rise to the mismatch between heat losses and heat gains in this method are taken into account through the introduction of utilization factors for heating and cooling.

Calculations of the energy consumption of the windows and energy consumption for space heating and cooling are based on considering the entire building as a single thermal zone, although the user has the option of providing input data for windows in several rooms. To construct the thermal model of the entire building in this step, only simple input data, such as the heated floor area, floor-to-ceiling height, thermal transmittance of the building envelope components (UA value), internal heat gains, infiltration rate, ventilation rate, use of heat exchanger, and heating and cooling set points are required. As suggested in EN ISO 13790 (CEN, 2008), the internal heat capacities of the different building components are taken into account by one effective heat capacity for the entire building.

As a starting point, input with regard to the internal heat gains, infiltration rate and ventilation rate are constant values for both the heating and cooling season. However, experienced users have the option to change this.

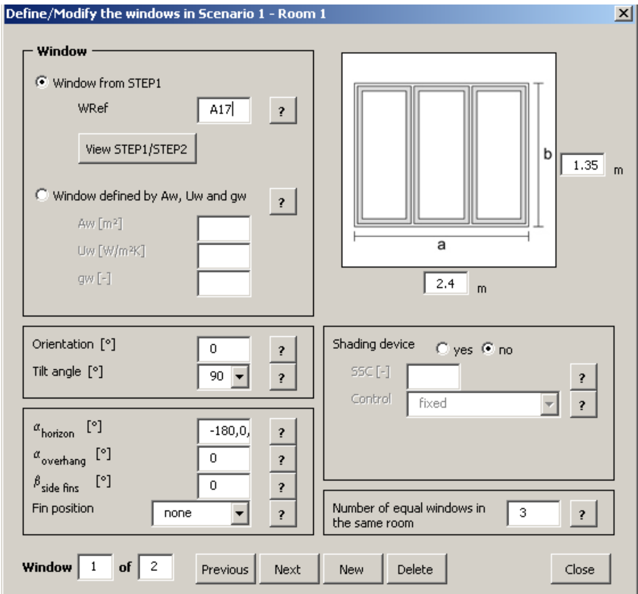

Figure 19: Illustration of input data needed for definition of windows in Step 2.

Windows for the specific building can be selected based on Step 1, or the user can define new windows by providing area A_w (m^2), thermal transmittance U_w(W/m^2K), and total solar energy transmittance g_w. To calculate the energy consumption of the windows in a specific home, the orientation, tilt angle, external obstructions from the horizon, overhangs and/or fins, solar shading coefficient, and control strategy for solar shading also need to be defined for each window, see Figure 19. In Step 2, the user can select between solar shading that is fixed or movable. If the shading device is fixed, the solar shading is activated the entire year. However, if the shading device is movable, a utilization factor is used to simulate the in-use time of the shading device for situations where the solar radiation exceeds 300 W/m^2, see Equation 2. However, this can be changed by experienced users.

$$F_{sh,with} = \frac{\left(\sum_{if\ I>300W/m^2} I\right)}{\sum I} \qquad (2)$$

The total solar radiation on each window is calculated in accordance with well-documented methods for estimating direct, diffuse and ground reflected solar radiation (Scharmer and Greif, 2000, Perez et al., 1990). The solar radiation is also corrected to take into account its dependency on the incidence angle (Scharmer and Greif, 2000). However, calculations of the incidence angle have been simplified in WinDesign by just calculating one incidence angle for the midpoint of the hour instead of using an average incident angle for the hour in question. Furthermore, in Step 2, the total solar radiation on each window is summed into a monthly average value.

Shading from exterior obstructions and overhangs and/or fins is calculated in accordance with EN ISO 13790 CEN, 2008). However, WinDesign does assume that shading from overhangs and fins only affect the direct and diffuse radiation and not the reflected part of the radiation.

After the calculation of the total solar radiation on each window, the energy consumption of the windows during the heating and cooling seasons ($E_{windows,HS}$, $E_{windows,CS}$, kWh/m^2) can be calculated using Equations 3 and 4.

$$E_{windows,HS} = \sum_i (U_{w,i} \cdot A_{w,i} \cdot G_{HS} - \eta_{gn,HS} \cdot F_{sh,ob,i,HS} \cdot A_{sol,i,HS} \cdot I_{sol,i,HS}) / A_{floor} \quad (3)$$

$$E_{windows,CS} = \sum_i (F_{sh,ob,i,CS} \cdot A_{sol,i,CS} \cdot I_{sol,i,CS} - \eta_{ls,CS} \cdot U_{w,i} \cdot A_{w,i} \cdot G_{CS}) / A_{floor} \quad (4)$$

For calculation of energy consumption for space heating and cooling, we refer to the equations in EN ISO 13790 (CEN, 2008).

Step 3: Hourly calculation of energy consumption and thermal comfort in a room

In Step 3, the thermal indoor environment is evaluated on an hourly basis for one or more rooms/thermal zones (or the entire home modelled as a single zone) for the scenarios defined in Step 2. The results are represented in terms of the number of hours with a temperature above a user-defined maximum comfort temperature for each room/thermal zone, and the temperature development can also be graphically represented. In addition to the evaluation of the thermal indoor environment, Step 3 includes an hourly calculation of energy consumption for space heating and cooling needed to achieve the desired indoor temperature and a method for estimating the electricity needed for artificial lighting in each room. As a basis for the hourly calculation, the 'simple hourly method' described in EN ISO 13790 (CEN, 2008) has been used. This method is a simple dynamic calculation method based on an equivalent resistance-capacitance (5R1C) model, see Figure 20.

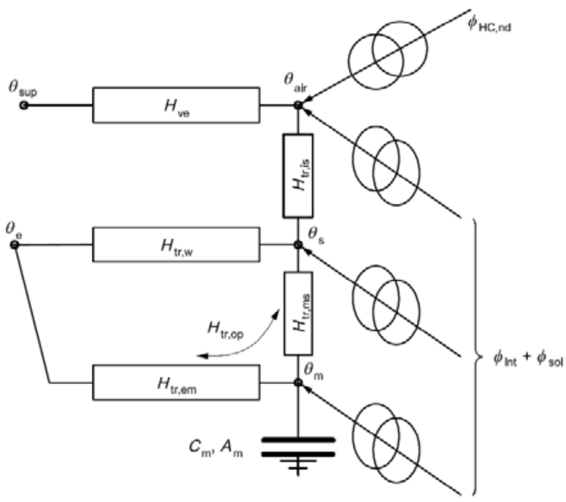

Figure 20: Illustration of the 5R1C equivalent model used for simple hourly dynamic calculations in EN ISO 13790.

The implementation of the equivalent RC-model in WinDesign is based on the independent multi-zone calculation defined in EN ISO 13790 (CEN, 2008). This means that no thermal interaction between the rooms is taken into account. To set up the equivalent RC-model for the various rooms in the building, additional information is needed about the total thermal transmittance of the building envelope and the internal floor area of each room. The user must also specify whether venting is used to cool the building and when the venting is activated. Furthermore, the systems defined in Step 2 (solar shading, ventilation, use of heat recovery, bypass of heat recovery, heating and cooling) can also be activated (or deactivated) to control the thermal indoor environment and calculate the energy consumption for space heating and cooling. The control strategy is based on using minimal energy for heating and cooling systems. More details can be found in Paper III.

To estimate the electricity needed for artificial lighting, the amount of electrical power needed to maintain a certain level of light in each room is calculated based on the daylight factor (DF) inside each room. WinDesign does not include a daylighting module, so the daylight factor has to be calculated using additional software. The calculated DF is then used to determine the light level at a set point, which is used for control of the electric light. The amount of artificial light needed to supply sufficient light at the set point is then calculated based on equation 5. Besides this, a time control is included to ensure that the lighting system is turned off outside occupancy hours. Further details on the control can be found in Paper III.

$$P = \begin{cases} \dfrac{P_{max} \cdot I_{setpoint}}{I_{thresholdvalue}} & if\ I_{setpoint} \leq I_{thresholdvalue} \\ \\ P_{min} & if\ I_{setpoint} > I_{thresholdvalue} \end{cases} \qquad (5)$$

Step 4: Economic evaluation

In Step 4, a simple economic evaluation, based on the criterion of the cost of conserved energy (CCE), can be made to compare costs and savings for the various design scenarios defined in Step 2 and Step 3. With one of the scenarios defined in Step 2 or Step 3 selected as reference scenario. The CCE (monetary unit/kWh) for the other scenarios is calculated as follows:

$$CCE = \frac{I - I_{ref}}{E_{ref} - E} \cdot \frac{d}{1 - (1 + d)^{-n}} \qquad (6)$$

The user can compare the results from the calculations for the various scenarios with the price of the energy source used to provide heating and cooling to the home. The CCE will then indicate whether it is cheaper to save energy or to consume it, see also *Section 2.4.4*.

4.2.2 Import capacity from ArchiCAD

As an advance in the use of WinDesign and of analysis of energy use and thermal indoor environment in general as an integral part of the early design phases, an IFC (Industry Foundation Classes, buildingSMART, 2011) collector has been implemented in WinDesign (ref Rune thesis), through which information stored in a Building Information Model (BIM), in this case ArchiCAD, can be extracted and utilized in WinDesign, which allows WinDesign to act within the BIM-process, see also *Section 4.2.3* for an application. The strategy for transfer of data between the BIM-model and WinDesign is shown in Figure 21.

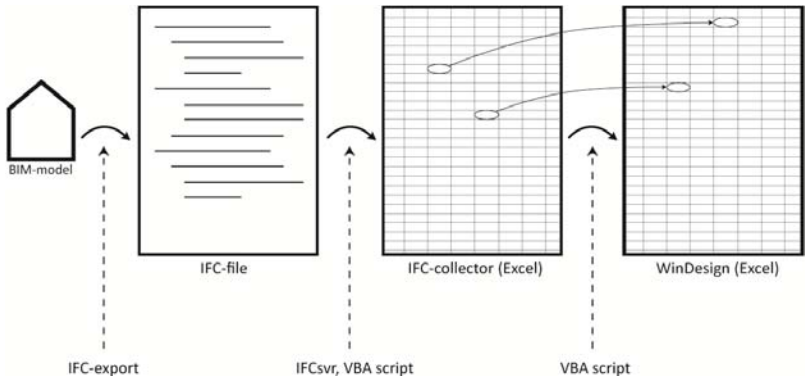

Figure 21 Illustration of the IFC import strategy from the BIM-model to WinDesign through the IFC-collector

The IFC collector is based on the use of the open object orientated file format IFC 2x3. Many BIM-applications are capable of exporting this kind of IFC-file, but they often have different IFC-export settings and algorithms. Furthermore, BIM-models may contain lots of information that is not needed. Therefore, the BIM-model in ArchiCAD should be created within a certain set of boundaries and only developed to a certain information level to ensure that the information stored in the IFC collector complies with the input required in WinDesign. In its current form, the IFC capacity for WinDesign has also only been developed as an import function. Design alternatives found by the analyses in WinDesign then need to be manually adjusted in the BIM-model. To increase the interaction between the BIM-model and WinDesign, a future version should also include an export function.

4.2.3 Application of the tool

WinDesign has been used for a wide range of applications. In Vanhoutteghem and Svendsen (2011), the tool was found useful for comparison of the energy performance and thermal indoor environment of a number of state-of-the-art windows implemented in a house constructed in accordance with the Danish building code requirements for 2020. Among other things, the results showed that merely looking at NEG based on the use of a short heating season for the calculation of NEG in 2020 implies that better windows than are on the market today will be needed to further reduce space heating demand, but this approach does not take into account the increased risk of overheating. On the other hand, the NEG calculations for 2020 buildings give better estimations of useful solar gains in the heating season.

The use of WinDesign has also been at the core of a number of master projects dealing with finding optimal window sizes in low-energy single-family houses from the perspective of energy use, thermal indoor environment and daylight. In relation to this, WinDesign was also used for documentation of thermal indoor environment in addition to documentation of energy consumption in Be10 (DBRI, 2013). Simulations with regard to daylight were often performed in Daylight Visualizer (DV, 2013), which is a simple application for daylight design and analysis that can provide the user with daylight factor maps and photorealistic rendering of daylight situations for a specific building design.

Other applications are the use of WinDesign in combination with a tool for cost-optimization and the use of WinDesign in a BIM-based design process. Both applications are described in more detail below.

Method for economic optimization of energy performance and the indoor environment in the design of sustainable buildings

A study by Hansen and Vanhoutteghem (2012) presented a method for the economic optimization of the design of new low-energy residential buildings that takes into account the indoor thermal environment and is suitable for use in the early stages of building design.

The process in the method relies on finding a cost optimal building design, based on an approach that uses the criterion of cost of conserved energy (CCE) to find economically optimal design solutions according to a targeted energy frame (Petersen and Svendsen, 2012, Hansen and Vanhoutteghem, 2012) in Microsoft Excel. The solution is then exported to WinDesign, where a parametric analysis can be performed to make sure that a good indoor thermal environment is obtained, see Figure 22. If any changes need to be made to ensure a good indoor environment, iteration between the two programs must be performed.

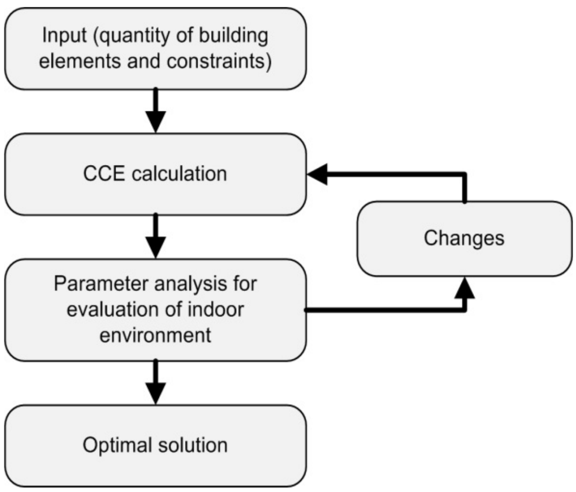

Figure 22: Flowchart of the method.

Using a case example featuring the optimization of a typical single-family house, Hansen and Vanhoutteghem (2012) show how the method is able to generate a qualified estimate of an economically optimal solution with a good thermal indoor environment, which can be used as a starting point for detailed optimization and iterative design with other advanced simulation tools. The results in the example also show that, to ensure that buildings reach low energy consumption at minimum extra cost, a further development of appropriate products and solutions for various building elements will be required and that they will have to be made available on the market at competitive prices.

The method suggested by Hansen and Vanhoutteghem (2012) was later elaborated to take into account the use of daylight (Grøn and Roed, 2011). As a first step in this method, window sizes that were optimal from the daylight perspective were found in Daylight Visualizer (DV, 2013). In the method suggested by Hansen and Vanhoutteghem (2012), the quantity of window area as input for the CCE calculation is chosen according to national guidelines on providing enough daylight as a reasonable starting point. If parameter analyses in WinDesign show that smaller windows, or windows with a lower visible light transmittance are required, an additional daylight analysis can be carried out.

Design process method for using BIM and integrated design in energy renovation projects

As in new buildings, BIM and integrated design could be used to improve the energy-efficient retrofitting practice and decision making. By using the IFC-capacity between WinDesign and ArchiCAD, supplemented with daylight analysis in Daylight Visualizer, Andersen (2010) developed a design process method that combines the use of BIM and integrated design for energy-efficient renovation of small-scale renovation projects in the early design phases (pre-design and concept design), see Figure 23. Daylight Visualizer was used because it was already equipped with an import function to communicate with BIM-models (DV, 2013).

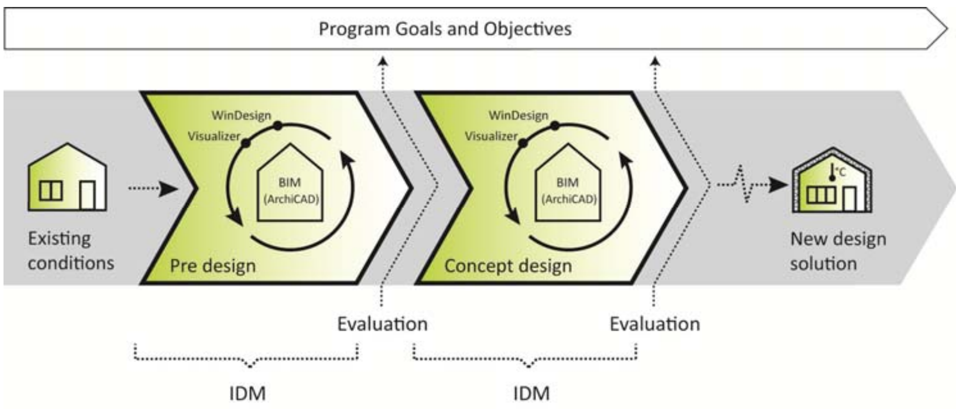

Figure 23: Illustration of the integration of ArchiCAD, WinDesign, and Daylight Visualizer in the pre design and concept design phases of an energy renovation project.

The method is based on the use of Information Delivery Manual (IDM) process maps, because they can help create a well-structured design process and structure information flows and activities related to the use of BIM (Wix and Karlshoej, 2010, ISO, 2010). Using IDM, Andersen (2010) investigated what information is required, who the participants are, what activities need to be performed, and how these can be structured to utilize the potential of BIM and integrated design in an energy renovation process.

Figure 24 illustrates a chronological progression of the different activities and information flows in the pre-design phase, starting with a request from the client and ending with a potential design solution. For each of the activities and information flows in the process, Andersen (2010) also defined exchange requirements (information that needs to be exchanged) and functional parts (defining the information that supports the exchange requirements). Various consultants, such as a cost consultant, an architectural consultant, a structural consultant, a BIM- consultant, and an energy consultant, are involved and carry out different activities during the design process. In small-scale renovation projects, some of these activities might, of course, be carried out by the same person.

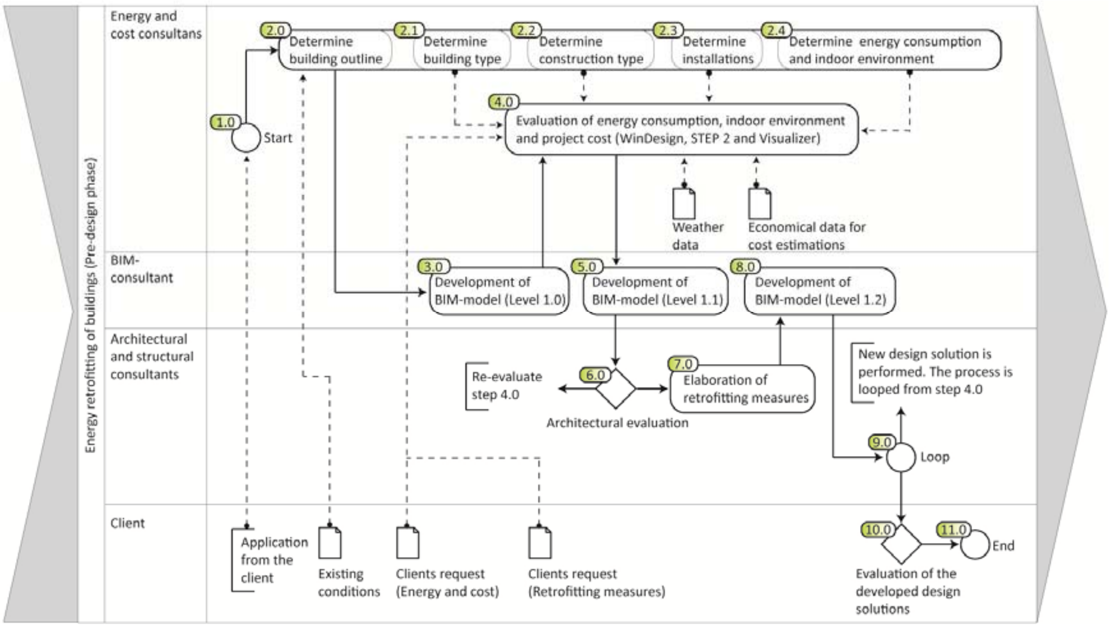

Figure 24: Process map illustrating activities and information flow in the pre-design phase.

The usability of IDM process maps and the potential of using WinDesign and Visualizer in a BIM-based design process were tested for the renovation of a single-family house and a simple office building. In general, it was found that the proposed IDM is a useful method for integrating BIM-based energy analysis and evaluating the indoor environment in the early design phases of an energy renovation process. Furthermore, Andersen (2010) documented that potential design solutions for the renovation of a single-family type house and a simple office building could reduce the primary energy use by 45% and 53%, respectively, while ensuring a good indoor environment.

4.2.4 Validation and inter-model comparison

This part gives the results from validation and inter-model comparison of WinDesign. Steps 2 and 3 in WinDesign are based on the use of the seasonal quasi-steady-state calculation and the simple hourly dynamic calculation method, respectively, as defined in EN ISO 13790 (CEN, 2008). In this part, only the simple hourly method is considered. The widespread adoption of the quasi-steady-state method means that the accuracy of the method has been investigated and compared with results from dynamic simulation tools in several studies (Jokisalo and Kurnitski 2007, Corrado and Fabrizio 2007, Orosa and Oliviera, 2010, Panao et al., 2011). Results from these studies showed that the method is adequate in most cases for determining monthly heating and annual heating energy consumption, but has some weaknesses with regard to the prediction of cooling demand. This was also briefly illustrated in Paper III.

Following a suite of test cases defined in ANSI/ASHREA Standard 140 (ANSI/ASHREA, 2007), earlier validation of the simple hourly method implemented in WinDesign (Vanhoutteghem and Svendsen, 2011) showed results for heating and cooling demand that are comparable with the results from well-known building energy simulation tools such as TRNSYS (Fiksel et al., 1995) and ESP-r (ESRU, 2011) and showed that results obtained by the simplified method are sufficient for the early design phases. Figure 25 illustrates some of the results for heating.

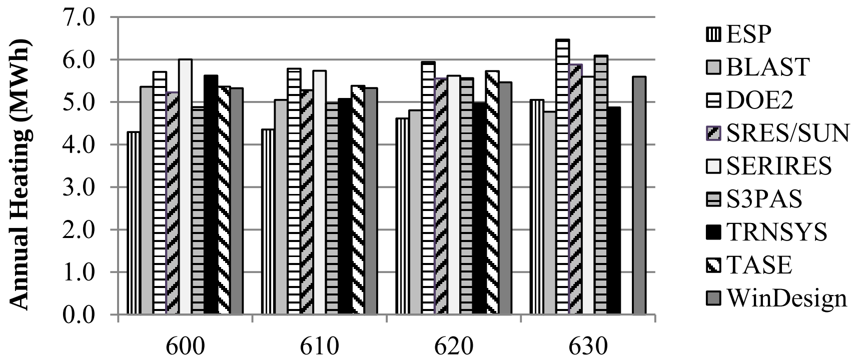

Figure 25: Annual heating requirement (MWh) for the 600-cases and results from WinDesign.

These tests, however, were based on a single-room. In Paper III, a more in-depth validation was carried out through comparison with results from the dynamic building simulation tool, EnergyPlus. Of interest was to see how the results compare for different zones in the single-family house, as the simple hourly method implemented in WinDesign does not consider any interaction between thermal zones. The 6-zone model of the single-family house described in Paper I was used for comparison with a 6-zone coupled thermal model in EnergyPlus heat transfer by thermal transmission between the different zones, and a 6-zone adiabatic model. To determine the energy demand under ideal conditions, the ‘ideal loads air system’, which has an infinite heating and cooling capacity, was used in EnergyPlus. Moreover, other inputs were harmonized for consistency in the compared models (Ballarini et al., 2010, Corrado et al., 2012). The results were compared for a range of parameters, such as insulation level, window size, window type, orientation and thermal mass. For more details, see Paper III.

The findings in Paper III showed generally good correspondence between annual results for cooling and heating demand obtained by using the simple hourly method and from dynamic simulation in EnergyPlus as most of the points comparing cooling and heating demand could be found between the two dotted lines in Figure 26 which represent a deviation of 15%. When compared to the coupled thermal zone model, largest deviations occurred for well-insulated buildings with regards to cooling demand and for large glazing-to-floor ratios and well-insulated buildings with regards to heating demand. However, a better fit for heating demand at large glazing-to-floor ratios was found from comparison with the adiabatic model.

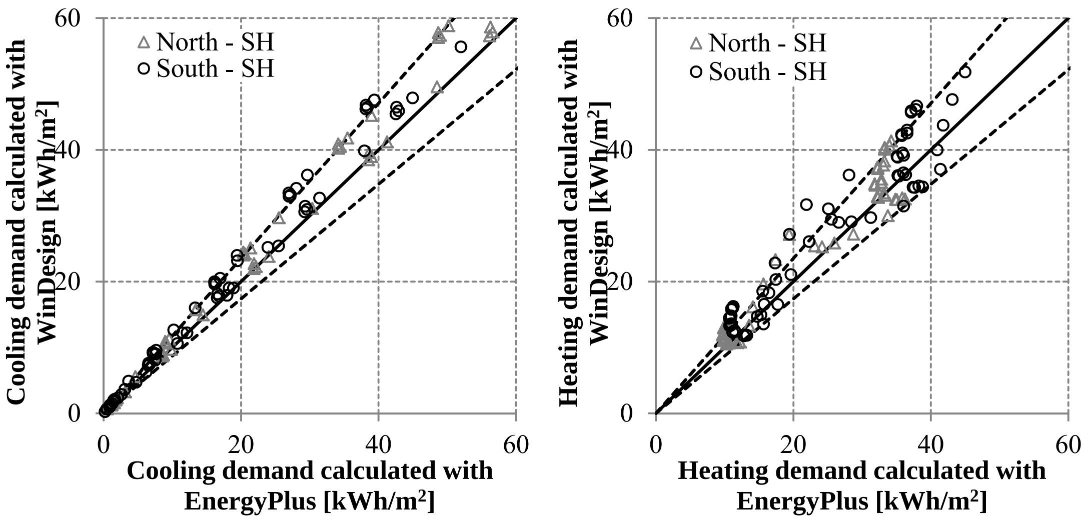

Figure 26: Comparison of cooling and heating demand obtained from the use of the simple hourly method (SH) in WinDesign with cooling and heating demand from dynamic simulations using a 6-zone coupled thermal model in EnergyPlus. The dotted lines represent a deviation of 15%.

Further investigations in Paper III also showed that using the simple hourly method gives reasonable results for heating and cooling demands compared to dynamic simulations based on the use of a coupled thermal zone model when considering the behaviour of the individual zones. With regards to the degree-hours with temperatures above 26^{o}C, the average differences and standard deviation between results was found slightly larger, but still acceptable. Investigation of temperature profiles showed, however, better comparison with results from the adiabatic model, especially for a well-insulated house and large glazing-to-floor ratios. For future use of the simple hourly method in design of well-insulated buildings, the implementation of a coupled thermal zone model might be considered. It was also identified in Paper III that even though all temperature profiles showed a similar trend, the dynamics of the different methods are different. The main reason could be due to the fact that the simple hourly method treats the thermal mass in a more simplified way than in dynamic simulation tools. This is especially important in well-insulated buildings and might warrant from further research.

4.3 One-stop-shop for renovation

To speed up the implementation of low-energy renovation of single-family houses and help the house owner with the design and decision-making process in connection with the renovation of his house, there is a need for a one-stop-shop concept in which a one-point-of-contact service provider (which could be a company or team of consultants and contractors) should help the house owner achieve a complete low-energy renovation. This means that all steps necessary for the renovation of the houses should be included, such as consulting, quotation for the work, financing, management of the contract work and follow-up.

This section introduces a method for renovation based on an ideal full-service concept and technical renovation packages targeted at different types of single-family house (see also Paper IV). The ideal full-service concept builds upon analysis of the few existing full-service concepts (Tommerup et al. 2010) for the renovation of single-family houses. Most of these concepts only entered the market recently, and their success has yet to be evaluated. Analysis (Tommerup et al. 2010, Vanhoutteghem et al. 2010) has shown that they can generally be improved by:

- Integrated analysis of the energy-saving potential and physical conditions
- Extensive analyses, such as thermography and blower door test, to be able to come up with trustworthy fixed price proposals with very few reservations
- Focus on handling of the homeowners needs and wishes and making it easy to buy renovation services (like in a kitchen studio) and more focus on the non-energy benefits
- Offering of the full range of technical solutions with focus on reducing heating demand before introducing measures to ensure energy-efficient energy supply
- Development of tools to quickly put together individual package solutions – based on the configuration of standard solutions – and including visualization of the renovation project for the homeowner.

4.3.1 Full-service renovation – ideal concept

The ideal full-service concept consists of five phases, going from the initial evaluation of the house, to extensive analyses, a proposal for package solutions, coordinated planning and execution and operation and management of the house after renovation, see Figure 27. However, the first step in implementation of a one-stop-shop model is that the company offering such a service must do some kind of marketing to inform the customers about the value proposition and create interest in the full-service concept. Various marketing strategies are investigated in Mahapatra et al. (2011).

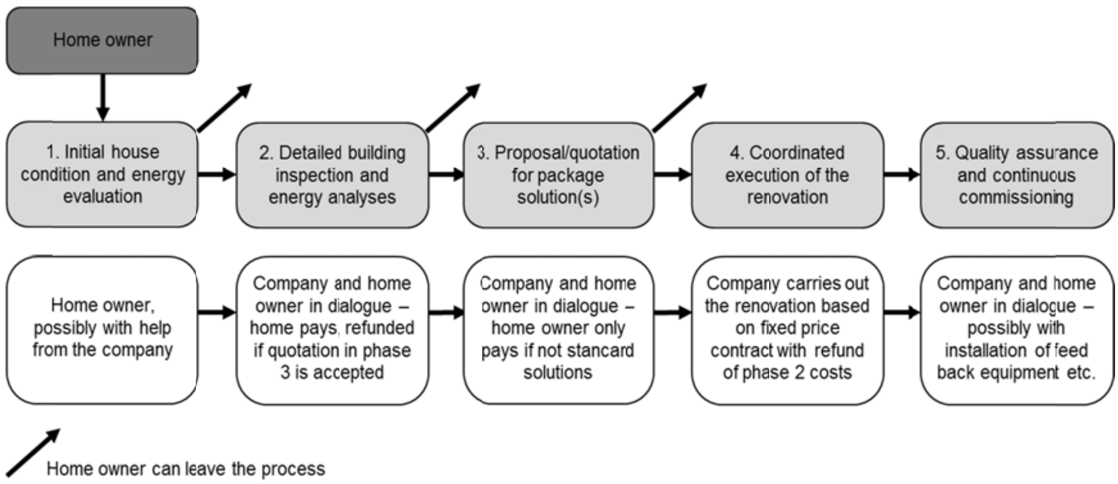

Figure 27: Ideal full-service concept for energy-efficient renovation.

The different phases in the concept are briefly described below.

Initial house condition and energy evaluation (phase 1)

House owners interested in the full-service concept will contact the one-stop-shop service provider/company. Initial analysis of the condition of the house and its energy-saving potential can be carried out by the house owner using an internet tool or a simple model provided by the service provider. Alternatively, the one-stop-shop service provider should visit the house to be renovated, conduct a free-of-cost preliminary building inspection and discuss with the homeowner the renovation requirements and the availability of subsidies. The house owner should also receive a rough estimate of possible savings and documentation/visualization of the effect of energy and non-energy benefits on the cost of financing the renovation. One possible basis for the analysis is an existing energy label, house condition report, drawings, pictures and other relevant documents.

Detailed building inspection and energy analyses (phase 2)

Based on the outcome of the preliminary analysis, some homeowners may opt for a traditional renovation process and avoid a more detailed energy analysis. However, others may be inclined to know more about the condition of the building and the potential to improve energy efficiency. This is an opportunity for the company to offer the option of a more comprehensive building inspection and detailed energy analyses by an independent actor (e.g. an independent energy consultant). The detailed analyses would be paid for by the homeowner, but refunded if a renovation package solution is bought from the company (phase 3). Extensive analyses, such as blower door testing and building thermography, will also provide the company with information that allows for a safe foundation for providing the homeowner with an evaluation report, including advice on how to improve the energy performance of the house in connection with the renovation needed, and fixed price quotations for the renovation work.

Proposal for package solutions (phase 3)

Based on discussion with the house owner about the evaluation report, proposals for renovation package solutions are put together, including a quotation for the work, financing and management of the contract work. Output from meetings with the house owner is used for further analyses and optimized combinations of technical renovation measures in the renovation packages. As output from phase 3, the homeowner receives a pre-project folder with fixed-price proposal(s) for these renovation packages, including visualization/documentation of their effect on:

- Energy use and energy bill – Total and annual investment cost versus savings in energy cost
- Household economy – short and long term, including the effect of the increased value of the house, etc.
- Indoor environment, e.g. indoor temperatures, draught, air quality and daylight
- Other durability and maintenance issues
- Alternative housing if the house needs to be vacated during renovation.
- Time line for the renovation work

The company should be able to carry out this phase within a few hours provided that the right system for the configuration of standard technical solutions is in place, including simplified but accurate calculation models for the estimation of energy savings and economic feasibility.

Coordinated execution of the renovation work (phase 4)

The house owner evaluates the packages and any remaining economic and financing issues are clarified and a contract for renovation work is signed. A detailed work description, including the time line, is set in place. If needed, drawings are prepared, and the contract work is carried out by the company and the affiliated professional group of consultants and contractors. The company obtains the necessary renovation permissions from the authorities and helps the homeowner apply for possible loan and/or governmental subsidies. The quality of the renovation work should be checked continuously to make corrections and make sure that the requirements defined are fulfilled. At the end of this phase, the renovated house is ready for use.

Quality assurance and continuous commissioning (phase 5)

The renovated house is inspected, e.g. by an independent certified energy consultant, to check the quality of work, and heating and ventilation systems are commissioned for at least two years. One important issue is to check that energy performance is continuously achieved and to make sure that the house functions optimally according to owner expectations and user needs. The energy performance of the building is regularly recorded and compared with the estimated potential for energy savings. The homeowner is presented with a follow-up evaluation report and a user manual on how to operate the building. Since user behaviour can have a large impact on energy use, it is important to present the homeowner with information on the consequences for energy use and indoor environment if the house is not operated as prescribed.

4.3.2 Concept for technical renovation packages targeted at different types of single-family houses

To achieve a low primary energy level, different technical renovation measures need to be combined and carried out during an overall or step-wise planned renovation; see also step 3 in the ideal full-service concept. The combination of several renovation measures into one package will also result in a higher level of cost-efficiency and speed up the renovation process.

Buildings vary in age, size, architecture, insulation standards, etc., so standard renovation packages might not be applicable to all types of building. The renovation process for different types of single-family houses may be very similar, but the technical solutions can be different. In Paper IV, a general concept for combining technical energy renovation measures targeted at different types of single-family houses into renovation packages is suggested based on previous work by the authors (Vanhoutteghem et al., 2010 and 2011). The concept, see Table 6, consists of various levels of packages for renovation as availability of skilled work force, financing mechanisms, and above all the awareness, interest and demographic characteristics of the occupant influence the form and degree of renovation. The sequence in which renovation measures are implemented is important, so first measures to reduce the energy demand are combined in packages, before adding systems for energy supply. This promotes more robust solutions because the most sustainable energy is saved energy.

Table 6: Packages of technical renovation measures

#	Package	Energy efficiency measures	Technical principles
R	Existing house	No energy efficiency measures	Traditional renovation to avoid physical degradation of components
1	”Easy-to-carry-out” measures	Insulation and sealing of building envelope, windows that allow for utilization of passive solar heat gains and daylight without excess overheating.	Minimized transmission and infiltration heat losses, utilization of passive solar heat gains, daylight, etc.
2	+ Efficient energy supply system	Heat pump, district heating, low temperature system, energy-efficient circulation pumps, insulation of heating pipes, etc.	Efficient energy supply for heating
3	+ Ambitious measures	Mechanical ventilation system with heat recovery (VHR), solar energy for hot water, etc.	Minimized ventilation heat losses and water heating demand
4	+ Extensive measures	Façade insulation that changes the appearance of the house, or measures that are far-reaching but allow for a large reduction in the primary energy use	Various

4.3.3 Case studies

First, energy savings by individual measures were documented for a so-called 'master builder' house constructed in 1927 and a standard detached house constructed in 1972, see Figure 28 and Figure 29. These categories of single-family houses have been identified as having the greatest potential for energy savings (see *Section 2.3.1*). Then, the impact of combining the individual energy-saving measures into packages as described in Table 6 on energy use, thermal indoor environment and cost-efficiency was documented using primary energy factors for the houses renovated in accordance with Class 2010 and low-energy Class 2015; see Figure 30, Figure 31 and Table 7.

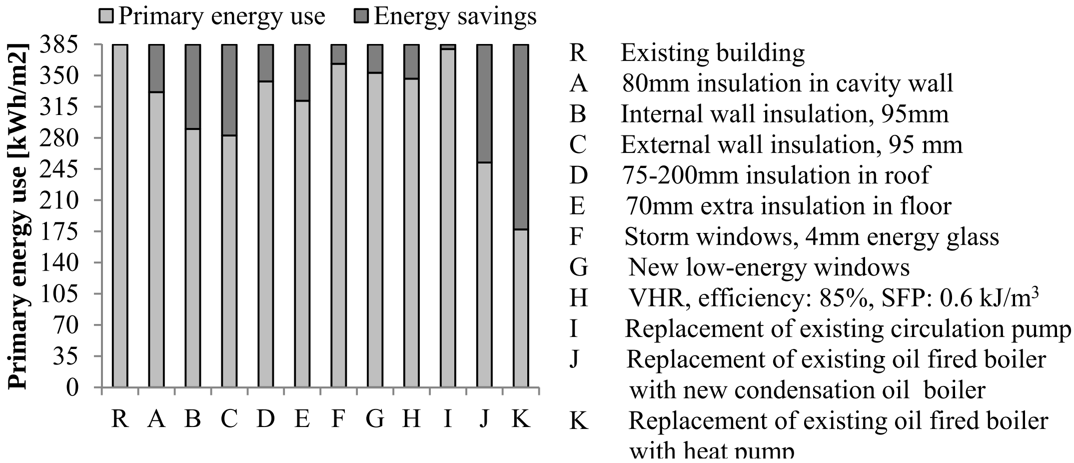

Figure 28: Primary energy use and savings (kWh/m² per year) for typical individual technical renovation measures for the master builder house.

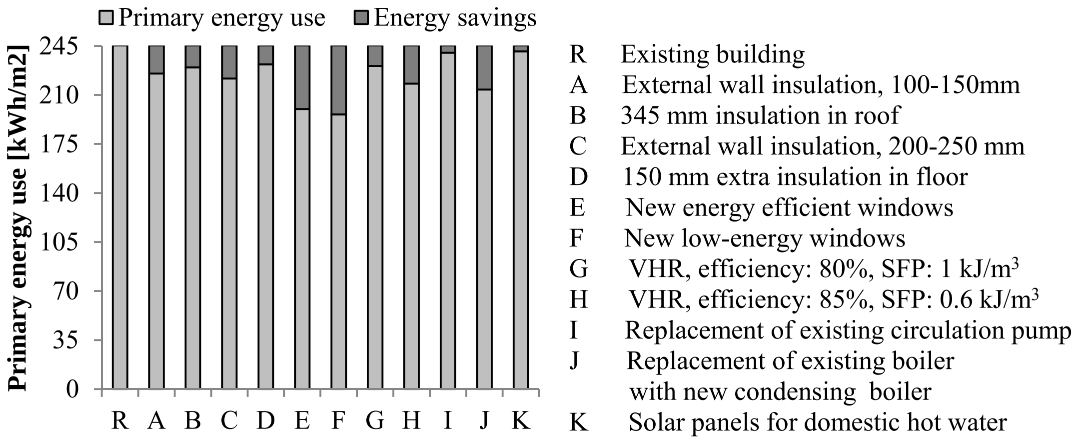

Figure 29: Primary energy use and savings (kWh/m² per year) for typical individual technical renovation measures for the house constructed in 1972.

As can be seen from Figure 28 and Figure 29, individual renovation measures are different for the two types of house. For example, many people regard the façades of 'master builder' houses as being worth preserving. Façades can be thermally improved by filling the cavity, e.g. with granulated mineral wool, whereas the façades of detached houses constructed during the 1960s and 1970s, which are characterized by having large roof overhangs, may be more likely to be renovated by adding external insulation.

From a technical point of view, adding external insulation is the best option for a 'master builder' house too, but should be seen as an extensive renovation measure because it influences the appearance of the house and might cause architectural problems with additional changes to the roof. A more detailed description of the houses and the renovation measures can be found in earlier work by the authors (Vanhoutteghem et al., 2010 and 2011).

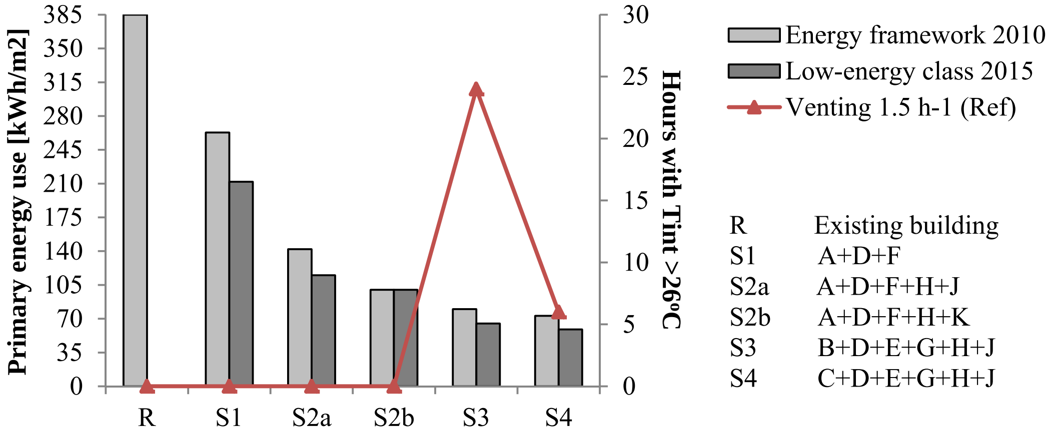

Figure 30: Primary energy use (kWh/m^2 per year) and thermal indoor environment for packages of technical renovation solutions applied to the master builder house.

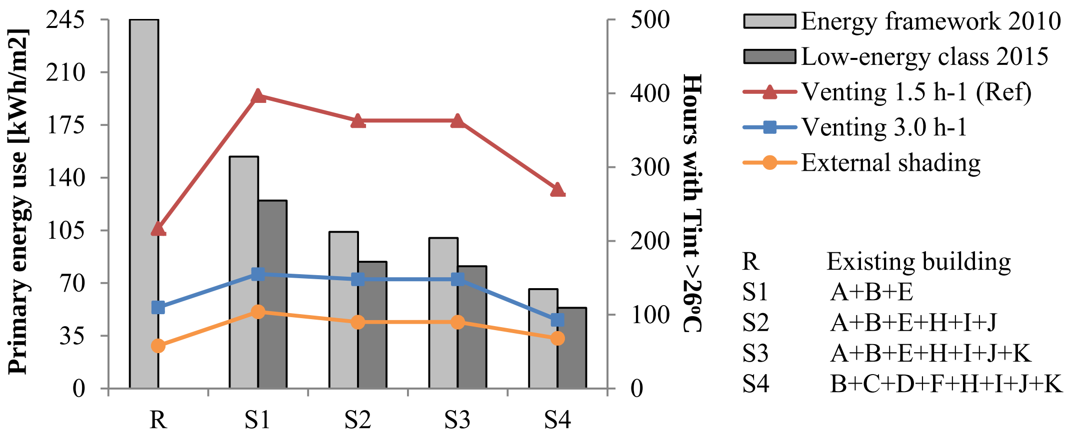

Figure 31: Primary energy use (kWh/m^2 per year) and thermal indoor environment for packages of technical renovation solutions applied to the house constructed in 1972.

From the analyses of combined renovation packages in Figure 30 and Figure 31, it can be generally concluded that typical Danish houses can be renovated to a level of energy performance which is comparable with the requirement for new houses today. However, the target for primary energy for new buildings today, calculated to approximately 63 kWh/m^2 per year for both houses (DEA, 2013), can only be reached with a complete energy-efficient renovation with extensive post-insulation and sealing of the building envelope, installation of a mechanical ventilation system with high efficiency heat recovery and low electricity use and an energy-efficient heating system (renovation package 5). Primary energy savings of 81% and 70% are then obtained for the 'master builder' house and the standard detached house, respectively.

To reach the target for buildings constructed in accordance with low-energy Class 2015 (approximately 36 kWh/m^2 per year for both houses), more ambitious measures or an additional supply by renewable energy would be needed.

Thermal comfort will generally be improved by insulation and air-tightness measures that will increase surface temperatures and reduce draught, e.g. from badly insulated windows. A ventilation system with heat recovery will also contribute to good thermal comfort with a draught-free supply of fresh air. However, one side effect of insulation measures that reduce heat losses may be some overheating, especially in detached houses constructed during the 1960s and 1970s, which can effectively be avoided by using external movable solar shadings and/or to some extent by a higher venting rate e.g. using automatically controlled windows. However, external shading is usually costly to install and may be sensitive to hard winds.

Results from cost analyses, see Table 7, show that all the renovation packages are very cost-effective when applied in the ‘master builder’ house since the house is originally heated by an oil-fired boiler and the price for oil was estimated at 0.90 DKK/kWh[2] (Vanhoutteghem et al., 2010). This is so even when the total investment cost for all renovation measures was used for CCE-calculations because none of the renovation measures applied in the different packages was needed for an improvement of the physical condition of the existing building. In the standard detached house, the windows needed replacement and work done to the bathroom and kitchen. Two different calculations were made: one where the total investment was used and a second where only the cost of energy-efficient measures was taken into account. Results are compared to a price for gas roughly estimated to 0.80 DKK/kWh[3] because the house is originally heated by a gas boiler. Looking at the results from the calculation of the total CCE, it is better not to renovate the house. However, when calculating the CCE based on the investment cost in energy-efficient measures, all scenarios are cost-effective and the effect of the two-fold benefit of renovation when only taking into account these investment costs in energy-efficient measures is clearly reflected in the results. From the results in Table 7, it can also be concluded that for both houses, it is more cost-effective to improve the building envelope, install a new boiler and VHR (package 2) than just to improve the building envelope (package 1).

Table 7: Calculation of cost-effectiveness of the different renovation packages.

		Existing building	**S1**	**S2a**	**S2b**	**S3**	**S4**
‘Master builder’ house	Total CCE (DKK/kWh)	Ref	0.29	0.26	0.24	0.28	0.26
Standard detached house	Total CCE (DKK/kWh)	Ref	2.43	1.75	-	1.78	1.65
	CCE energy-efficient measures (DKK/kWh)	Ref	0.72	0.65	-	0.7	0.72

[2] 1 DKK = 0.13 €
[3] 1 DKK = 0.13 €

5 Discussion

With the aim of reducing energy consumption in the Danish building stock, the present research investigated both the design of new buildings and the renovation of existing buildings. This chapter discusses the results of these investigations.

5.1 Window design in low-energy buildings

For the design of new buildings, the relationships between various window parameters, such as glazing-to-floor ratio, orientation and glazing properties, were studied.

5.1.1 Choice of window size and orientation

In contrast with existing guidelines and current practice for window design, it was found that the choice of window size and orientation is no longer a big issue from the perspective of space heating demand as long as low glazing U-values are used. Because of this, windows can be positioned in the façade of well-insulated buildings with considerable architectural freedom. It was also shown that to achieve optimal daylight levels in all rooms of these buildings and a good thermal indoor environment, windows can be chosen on a room by room basis with the choice of glazing-to-floor ratio based on daylight requirements. In relation to this, it was found that in south-oriented rooms, overheating and the choice of g-value are highly related to glazing-to-floor ratio. Whereas in north-oriented rooms, a high g-value is needed for all glazing-to-floor ratios to reduce space heating demand, this was found to be no longer important in south-oriented rooms in well-insulated housing. In fact, when glazing with a high light transmittance and a low U-value is used, a good match was found between the maximum g-value allowable from the perspective of heating demand and the g-value at which the reduction in space heating demand with increased access to solar gains stagnates. This shows how a successful window solution depends on the interrelationship between products and design. Another example is the potential design conflict in side-lit deep or narrow south-oriented rooms. The choice of such room dimensions means that either thermal comfort or daylight must be compromised if additional cooling or alternative options, such as increased venting (for example using cross ventilation), special shading systems, etc., are not used.

5.1.2 Dynamic solar shading vs. permanent solar shading

From comparison of dynamically controlled external solar shading and the use of glazing with solar-control coating, it was found that glazing with solar-control coating could very well be used as a robust, user-friendly and cost-effective alternative to the use of dynamically controlled solar shading to avoid overheating in south-oriented rooms. However, when glazing with high U-values (0.9 W/m^2K) is used with large glazing-to-floor ratios, the use of a glazing with high g-value in combination with dynamically controlled solar shading would lead to relatively high benefits in terms of space heating demand compared to the use of glazing with solar-control coating and low g-value. On the other hand, at smaller glazing-to-floor ratios, the difference in space heating demand decreases and both dynamically controlled shadings or glazing with solar-control coating could be used.

Dynamic solar shadings can be very costly to install and maintain, and might not always be the house owners' choice when aesthetics are considered. Furthermore, when these shadings are not operated as intended, this can result in reduced occupant comfort. On the other hand, glazing with solar-control coating has a light transmittance which at maximum is twice the solar transmittance, which means that larger window areas are needed to allow the same use of daylight as with clear glazing or when dynamic solar shading is not active. Moreover, one should keep in mind that some types of solar-coating can give a slight tint to the glass, which might be undesirable. The decision on whether to use external solar shading or glazing with solar coating should be left to the building owner. In the end, it does not matter which option is used, as long as prevention of overheating is integrated in the design process from the beginning.

5.1.3 Climate-dependent daylight target vs. CBDM

When considering various room geometries that can achieve the daylight target without overheating, the use of a climate-dependent target (DF_{target}) shows that glazing-to-floor ratios of approximately 17-25% are needed to achieve the specified daylight target for light transmittances of 0.7–0.5 in both north- and south-oriented rooms under the assumption that ideal window positions from perspective of daylight are used. The use of the climate-dependent target takes into account location, but does not take into account realistic sun and sky conditions because it is based on evaluation of the daylight target under a CIE overcast sky. Using the climate-dependent target, greater flexibility in the choice of window size and geometry was found in north-oriented rooms than for south-oriented rooms.

From comparison of calculations based on the use of the climate-dependent target with calculations based on CBDM, it was found that for the two orientations to have comparable daylight availability over time under realistic sun and sky conditions, either the glazing-to-floor ratio towards the south must be decreased (less ambitious target) or the glazing-to-floor ratio towards the north must be increased (more ambitious target). For south-oriented rooms, the use of the more ambitious target corresponds to the use of glazing-to-floor ratios as found by using the climate-dependent target. When the less ambitious target is used, glazing-to-floor ratios to fulfil the daylight target are found that are smaller than optimal from the perspective of heating demand. As the risk of overheating is close to insignificant in north-oriented rooms, the use of larger glazing-to-floor ratios poses no problem, so the choice to go for the more ambitious target for daylight availability seems an easy one to make. If low glazing U-values are used, the larger glazing-to-floor ratios needed to achieve the more ambitious daylight target might actually help reduce space heating demand. However, for high glazing U-values, larger glazing-to-floor ratios mean a significant increase in space heating demand and the use of a climate-dependent target might be a good compromise if we do not need the same amount of daylight in north and south-oriented rooms.

Apart from more daylight availability, the use of a climate-based daylight evaluation increases the choice of room geometry for both orientations. With the ambitious daylight target this advantage is still present, but less pronounced. It could, however, be concluded that the use of CBDM is needed to illustrate the 'real' space of solutions for both orientations. However, further studies, including on visual comfort in south-oriented rooms and the possible health effect of daylight, will be needed to determine how comparable targets for north- and south-oriented rooms can be set in homes. At this stage, the use of a climate-dependent target might also be considered a valid approach because architects and designers do not always have the knowledge or expert tools to calculate the available daylight using CBDM in the early design phases.

5.1.4 Usability of charts illustrating the 'space of solutions'

The selection of beneficial window solutions in terms of space heating demand, thermal environment and daylight availability requires knowledge about the properties of the specific products as well as the various geometrical factors related to their application (design), such as window size, room geometry and orientation. The parametric analyses and the charts illustrating the space of solutions are an invitation to an open discussion of the link between various design and performance parameters as well as the options and potential conflicts related to window design in 'nearly zero-energy' houses. Furthermore, the research described in this thesis is an example of an approach by which window solutions with minimum space heating demand can be chosen in a space of solutions for each geometry defined by targets for minimum daylight availability and overheating by using these charts.

The charts also highlight potential design conflicts in deep or narrow south-oriented rooms, because either thermal comfort or daylight must be compromised when only side-lit windows are used. Conflict situations like this can lead to a discussion on the performance parameters and the chosen targets in the charts. In principle, these can be tested for sensitivity to e.g. different insulation thicknesses, different user patterns and adaptive models for thermal comfort, different ventilation systems, and different daylight targets. In the Danish climate, it was possible to have window design fulfilling the targets for daylight and overheating without the use of mechanical cooling and with a moderate venting rate. However, especially in warmer climates, where mechanical cooling is needed to avoid overheating, the value of daylight compared to the energy used for cooling may give rise to several discussions, such as whether it is reasonable to dimension the window sizes in south-oriented rooms on the basis of targets for daylight availability under overcast situations.

The research described in this thesis also evaluated daylight as an independent performance parameter, rather than expressed in terms of a reduction in energy used for artificial lighting. As the energy consumption in residential buildings decreases, however, energy used for artificial lighting might come to represent a large share of the total energy consumption if no appropriate energy-efficient lighting and control system is used.

5.2 WinDesign

The thesis proposes a simple tool, called WinDesign, originally designed to help architects and engineers with the selection of window design in residential buildings.

5.2.1 Role of the tool in the design process

Through a 4-step method, different energy-efficient windows can be compared. Following the four steps, the user is able to select a window design, based on an evaluation of NEG, energy consumption, thermal indoor environment, cost, and to a certain extent daylight (based on the electricity consumption for artificial lighting). With the further development of the tool, it can now also be used to carry out a quick parametric study for other building components and generally document and predict building performance in the early design phases. This was demonstrated through applications of the tool in *Section 4.2.3*. For example, the tool was used for documentation of thermal indoor environment in addition to documentation of energy consumption in Be10. The role of the tool in the design process could thus be two-fold.

Based on the use of simple methods and limited required input, the proposed simplified tool enables the user to carry out an integrated energy use and indoor environment simulation of design solutions relatively fast compared to more advanced tools. Because its input requirements are limited, the user could benefit from using the tool in the early phases of the design process, where the most important decisions are made. The workflow in the tool also supports this because each step in the tool increases in level of detail, which supports design decisions throughout the design process. At the beginning of the design process, for example, not all the building parameters are known. Often, the most important thing is to be able to see the orders of magnitude and be able to compare various solutions rather than make an exact calculation. Nevertheless, even though the tool is based on the implementation of simple methods, it showed overall good agreement with results from more advanced tools and compared well with results from more detailed simulations in EnergyPlus. However, the methods in the tool could benefit from additional research when used for design of very well-insulated buildings with large glazing-to-floor ratios.

5.2.2 WinDesign – Application

It has been shown that WinDesign can be used for a range of applications in building design. Besides the use of WinDesign for its initial purpose: the selection of windows in a residential building, one example included in this thesis illustrates how WinDesign can be used for the documentation of thermal indoor environment in combination with a tool for the cost-optimization of a building design. The aspect of cost plays an important role in both the design of new buildings and the renovation of existing buildings. In new building design, architects, engineers and builders face the challenge of designing better performing buildings at minimal extra cost than new buildings today, and cost-efficiency also plays a major role in renovations.

It is already possible to compare the cost-efficiency of various design proposals in WinDesign, but in the future it might be useful to integrate the tool for cost-optimization in WinDesign and use it as a starting point for further evaluation. This should be fairly easy to accomplish because both tools are built in the Microsoft Office Excel environment. Other adjustments to WinDesign can also easily be implemented due to the open access Microsoft Excel and Visual Basic-based programming. One such example is the integration of an import capacity from ArchiCAD.

By making use of this capacity, it was possible to demonstrate the use of WinDesign in a BIM-based design process. In this design process, data from a BIM-model in ArchiCAD was used in WinDesign and Daylight Visualizer for the design of energy-efficient renovation. The interaction between the BIM-model, WinDesign and Daylight Visualizer, although not ideal, enabled integrated evaluation of the energy consumption, thermal indoor environment and daylight in the early phases in the design process. It is expected that the time and effort to build up the BIM-model will be well-spent because the model could also be used later in the design process and during the construction and operation phases.

5.2.3 WinDesign – Limitations

In this part, limitations to the application of WinDesign will be discussed. Other limitations related to improvements in the user-friendliness of the program, such as including a database for building components other than windows, alternative models for the evaluation of thermal comfort and solar shading strategies/types, are not included here, but should be considered for the further improvement of the tool.

To stimulate analysis of energy use and thermal indoor environment in general as an integral part of the early design phases, WinDesign has been provided with an IFC capacity. However, because room geometry is not defined in WinDesign, this capacity exists only as an import function. In its current form, this capacity exists only as an import function. To be able to export data from WinDesign to a BIM-model, definitions of room width, depth and the position of windows in each room need to be included in WinDesign. On the other hand, the fact that geometry is not taking into account limits the input data and thereby the time required to create the thermal model of the building.

As mentioned, the simple data input required by WinDesign has its advantages, but at the same time it also limits the complexity of its analysis. Inputs such as domestic hot water, efficiency of heat supply systems, etc. have not been implemented in its current form, which means that only results for space heating/cooling and electricity use for artificial lighting can be obtained. However, these inputs can easily be implemented.

To find out how much electricity is required for artificial lighting, the user needs to calculate the daylight factor at a user-specified reference point using additional software. In this connection, there are several issues. First of all, it is only possible to use the daylight factor for one reference point in a room in WinDesign. Second, estimations based on the daylight factor are usually based on the use of the standard overcast sky, which may result in a single-value that under- or overestimates the electricity needed for artificial lighting. However, this is partly corrected for in WinDesign because it takes into account external illuminance based on weather data for the specific location in its calculation of the final electricity needed for artificial lighting, see Paper III. Third, the user needs to have additional knowledge on daylight modelling. As can be seen from the use of WinDesign in a number of master projects, students often choose to use Daylight Visualizer in combination with WinDesign because it is also an easy-to-understand and user-friendly tool. For future development, a link between these two programs could be established, or a daylight module could be implemented in WinDesign. The latter, however, would require extensive changes in the tool. As an alternative, other tools such as iDbuild (Nielsen et al., 2008) could be used. In this case, iDbuild could also be used for an optimal control of heating, ventilation and the use of solar shading based on weather forecasts. However, at present it is only possible to define one room, with only one side-lit window and no roof windows in iDbuild.

5.3 One-stop shopping for renovation

This thesis presents an ideal concept for implementing a one-stop shopping concept whereby a single actor offers a full-service renovation package. The purpose of such a one-stop shop is to help house owners with the design and decision-making process in connection with renovation of their house.

5.3.1 Implementation of the ideal concept

The implementation of the ideal one-stop shop concept should make it easy, simple and secure for the house owner to invest in a low-energy renovation. Following the concept, house owners will get a quality renovated house with little risk and responsibility. For a successful implementation of the proposed concept, however, it is essential for the service provider to understand the house owners' needs and wishes. For example, in Step 2 of the ideal concept, the house owner is provided with an evaluation report based on extensive analysis of the condition of the house. This report should include an estimation of the potential energy savings and economic implications for the holistic renovation needed. In some cases, the house owner may not have the means for a holistic renovation, so the company should also offer to make a detailed long-term plan for renovation, which optimizes the economic aspects in relation to the house owner's wishes and needs. Furthermore, the traditional market for renovation is very much a do-it-yourself-culture; so the renovation packages proposed should be flexible to handle a house owner's wish to contribute to the process of carrying out the work.

Business model and marketing strategies

Other aspects of successful implementation of the ideal concept are marketing and business strategies. Haavik et al (2010) identified that various types of actors, such as hardware supply chains, utility companies and contractors, could play the key role in a one-stop shop for the energy-efficient renovation of single-family houses. The service might also be provided by an existing company that wants to expand its business. From evaluation of the few existing one-stop shop models, Mahapatra et al. (2013) found that it is difficult to run such a business and identified the main barrier from the house owner's point of view to be the trustworthiness of the service provider and all the actors involved in the one-stop shop. This is because the service is new and may be perceived as risky by house owners. To improve trustworthiness, the service provider needs to be able to offer independent but quality advice to the house owner. Collaboration with well reputed research organizations or public bodies and the training of installers/sellers could also help build trust.

Furthermore, uncertainty about the level of energy savings after renovation due to varying occupant behaviour might discourage both the house owner and financiers from making energy-efficient investments. However, there are concepts for guarantees on energy savings for industrial and public buildings (the ESCO concept), which may also emerge for residential buildings. Alternatively, information campaigns and the availability of policy instruments in form of regulations and economic incentives may create house owner interest in energy-efficient renovations (Mahapatra et al. 2013). Another way is to provide public funding for demonstration projects. The ideal concept for a one-stop shop business model is currently being tested for the holistic renovation of two Danish single-family houses built in the period 1960-1970. Important experience will be gained from this, and the dissemination of results from these demonstration projects may contribute to a larger market for energy-efficient renovation.

5.3.2 Technical renovation packages targeted at single-family houses

As part of the ideal concept proposed in this thesis, renovation packages targeted at various types of Danish single-family houses were suggested and investigated in two case studies. Results from the case studies showed that both typical single-family houses could be renovated to a level of energy performance which is comparable to the requirements for new houses today. However, to reach this target, what is needed is a complete energy-efficient renovation with extensive post-insulation and sealing of the building envelope, the installation of a mechanical ventilation system with high efficiency heat recovery and low electricity use, and an energy-efficient heating system (renovation package 5). To renovate the case studies to the level that meets requirements for future buildings, it was found that more ambitious measures (better insulation materials and new components) or an additional supply from renewable energy would be needed, irrespective the building typology.

Cost-efficiency of measures

Carrying out a comprehensive low-energy renovation means a relatively large investment. The total investment needed to reach a low primary energy level and a good indoor environment after renovation has been calculated to be in the range of EUR 100,000 (DKK 750,000). Results from cost calculations have showed that if packages of technical energy efficiency measures are to be attractive for the homeowner, it is generally crucial to link them to normal renovation measures needed due to physical degradation of major building components, bad indoor environment or/and health problems. In this way, costs are not compared to energy benefits alone.

These cost calculations were based on the criterion of cost of conserved energy (CCE). Mahapatra et al. (2011) suggested that the method of "annual economic balance", i.e. savings minus repayments on a mortgage credit loan could also be used because this might be relevant for house owners who want to utilize cheap long-term financing based on equity. Moreover, it is also important to address the non-energy benefits of energy-efficient renovation, such as better and healthier indoor environment and comfort. Other benefits are the improved lifespan of structures, the increase in the value of the house, and less dependence on expected future higher energy prices.

6 Conclusion and outlook

This chapter provides an assessment of the objectives and hypothesis of the thesis, some concluding remarks on its findings, and some recommendations for further work.

6.1 Conclusion

The aim of this thesis was to contribute in the development of Danish low-energy residential buildings with good indoor environment. Both new building design and renovation of existing buildings were considered. As such, the objectives supported by the main hypothesis and sub-hypotheses in this thesis were three-fold:

- To provide insight into the relationship between various window parameters, and how these affect energy performance, daylight and thermal indoor environment
- To be able to select windows in a specific building based on integrated evaluation of energy performance and indoor environment
- To provide knowledge on how to update the existing building stock to meet future energy requirements based on an integrated approach and application of the full range of technical renovation solutions.

The main findings in this thesis can be summarised as follows:

SH1 The use of solar heat gains to reduce energy consumption for heating is not as important in well-insulated buildings as is traditionally believed. Accordingly, the choice of window size and orientation is no longer a big issue from the perspective of space heating demand as long as low glazing U-values are used. If an even window distribution is used in combination with an appropriate venting rate and solar control in critical south-oriented rooms, windows can be positioned in the façade of well-insulated homes with considerable architectural freedom.

SH2 Investigations into the relationships between various window parameters and their effect on space heating demand, thermal indoor environment and daylight showed that window solutions can be chosen on a room-by-room basis with the choice of glazing-to-floor ratio based on daylight requirements. To achieve a good thermal indoor environment and a minimum space heating demand, however, a high g-value is recommended in north-oriented rooms, and glazing with solar-control coating can be used as an alternative to dynamically controlled solar shading in south-oriented rooms.

SH3 The development and validation of a simple tool showed how windows can be selected with regard to energy use, thermal indoor environment, cost, and to a certain extent daylight (based on electricity consumption for artificial lighting) by using a 4-step method. The author suggests additional daylight analysis using other user-friendly and simple tools, such as Daylight Visualizer. Application of the tool demonstrated its usability in the early design phases.

SH4 A method for renovation based on an ideal one-stop shopping concept was presented. Through contact with a single actor, the house owner is provided with a full-service package including all the steps necessary for the renovation including consulting, quotation for the work, financing, management of the contract work, and follow-up. This helps house owners with the design and decision-making process in connection with a low-energy renovation of their house. As part of the method, renovation packages targeted at various types of single-family houses have been suggested. Results from two case studies showed that both typical single-family houses could be renovated to a level of energy performance which is comparable to the requirements for new houses today, but only if extensive post-insulation is combined with energy-efficient building systems.

To sum up, by answering the individual sub-hypotheses, the overall aim and objectives of the thesis have been achieved. However, some of methods and tools presented could benefit from further work to support the research findings.

6.2 Further work and recommendations

Further work and recommendations are summarised within the topic areas of each objective.

6.2.1 Window design in low-energy homes

The investigation into the relationships between the various window parameters was limited to the use of side-lit windows. Some conflicts arise in deep or very-narrow south oriented rooms, in which either daylight or thermal indoor environment must be compromised. This indicates the need for an investigation into the use of roof windows. Further studies related to other climates and locations should also be considered. In this connection, it has already been mentioned that some other performance parameters (e.g. heating and cooling need) and targets for the evaluation of thermal indoor environment and daylight might also be investigated. The target used for the main daylight evaluation in this thesis was chosen to reflect a specific location, but might benefit from further validation.

6.2.2 Tool for selection of window design

The application of the tool described in *Section 4.2.3* may inspire further efforts to enhance the integration of the simulation tool into the building design process. In this connection, it has already been mentioned that the IFC-import capacity would benefit from an export function. The tool could also benefit from a more detailed daylight analysis, either integrated, or stimulated through closer cooperation and an option for data exchange with a simple daylight simulation tool.

Other ideas to improve the user-friendliness and usability of the program were briefly mentioned in *Section 5.2.3*.

6.2.3 Renovation of existing buildings

If correctly implemented, the ideal one-stop shopping concept suggested should make it easy, simple and secure for the house owner to invest in a low-energy renovation. To speed up the implementation of the concept, the research in this thesis would benefit from further investigations into marketing strategies and incentive structures, such as increased tax on energy and/or subsidy programmes. It might also be interesting to look in more detail into long-term plans for low-energy renovation and how to ensure that the target for low energy consumption is reached because many house owners may not have the means for a holistic renovation.

The ideal one-stop shopping concept is currently being tested for the holistic renovation of two Danish single-family houses built in the period 1960-1970. However, to test and verify the concept and increase the market for energy-efficient renovation, more case studies are generally needed, including in the segment of single-family houses constructed before 1930. Furthermore, if the energy consumption after renovation is to meet the requirements for future new buildings, further research in other energy-saving measures and new materials will also be needed.

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Paper I

Modern insulation requirements change the rules of architectural design in low-energy homes.

Vanhoutteghem, L. & Svendsen, S.

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MODERN INSULATION REQUIREMENTS CHANGE THE RULES OF ARCHITECTURAL DESIGN IN LOW-ENERGY HOMES

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Abstract

In the design of very well-insulated homes, there is a need for a more nuanced design that takes into account winter and summer conditions. In this paper, we compare a traditional design for a typical Danish single-family house with large glazing areas oriented towards the south and smaller glazing areas towards the north, and a design with an even window distribution where the glazing-to-floor ratio is the same for each room. We found that the use of solar gains through south-oriented windows is not as important as is traditionally believed because, in well-insulated homes, space heating demand is not reduced much by having larger south-facing windows. Furthermore, we found that there is a g-value above which the extra solar gains through south-oriented windows do not help reduce space heating demand, and it becomes important to use solar shading or glazing with solar-control coating as a cheaper alternative to reduce overheating. Maximum window sizes from an overheating perspective were identified that are larger than the optimal window sizes for space heating demand. However, we show that the difference in space heating demand with optimal window size and with larger window sizes is small, so it is up to the building owner to decide whether or not he wants larger glazing areas to allow for more daylight. And windows can be positioned in the façade with considerable architectural freedom. However, we do recommend an even distribution of the glazing-to-floor ratio, because this generally provides an improved thermal indoor environment in south-oriented rooms and will ensure a better daylight level especially in north-oriented rooms. We also show that the optimal window size is influenced by thermal zone configuration and that there is a need for models in which a difference is made between zones with direct and with non-direct solar gains.

Keywords: fenestration, window size, orientation, glazing with solar-control coating, thermal zones.

1. Introduction

The tightening of energy requirements strengthens the focus on the design of buildings with low energy consumption. In Denmark, as in the rest of the European Union, building energy consumption represents between 30 and 40 per cent of the total energy consumption [1]. To comply with the principles of the Energy Performance of Buildings Directive [2], the Danish government agreed on a reduction of energy consumption in new buildings by at least 25% in 2010, 2015 and 2020, giving a total reduction of the energy consumption of new buildings of at least 75% in 2020 compared to 2006 levels [3]. To follow up on policy, architects, engineers and builders need to consider how future new buildings are to be designed and built. Moreover, they will also face the challenge of designing better performing buildings at minimal extra cost compared to new buildings today.

Passive solar design is often considered a central issue in the design of low-energy buildings because utilization of solar heat through the windows is, when properly oriented, a free way of reducing heating and cooling demand. On the other hand, windows are often seen as the weakest part of the building envelope because their overall heat transfer coefficient is larger than that of the other building envelope components. As such, window orientation, size, configuration and the thermal performance of the individual window components can greatly affect the energy use in buildings, which means it is important to select the right window design from the early stages of the design process.

Various studies have tackled the subject of selecting appropriate window size [4-6] and thermal performance of window types [7-8] in residential buildings in different locations. With regard to the energy needed for heating, these studies showed that orienting the largest glazing area to the south gives the best performance. Moreover, the overall energy needed for heating decreases with an increase in window size to the south. From a heating perspective, south-facing windows should therefore be as large as possible. Gasparella et al. [8] concluded, however, that savings on heating demand obtained from increasing the glazing area facing south are much less than the increase in cooling demand. Instead, solar transmittance appeared to be more important for heating and cooling demand. Persson et al. [9] showed that to reduce the risk of overheating and the energy needed for cooling in passive houses located in Sweden, there is an optimal size for windows facing south that is smaller than normally used. In contrast to previous studies, they also found that the size of energy-efficient windows in passive houses has no major effect on the heating demand during the winter and concluded that it would be possible to reorient the houses differently without losing too much energy. Furthermore, they suggested that instead of the traditional way of building passive houses, it should be possible to enlarge the glazing area in north-facing rooms. Findings by Morrissey et al. [10] tend to concur with this result. From a comparison of homes designed in accordance with current energy efficiency standards and future improved energy standards, they showed that more energy-efficient homes are less susceptible to effects of orientation. A study by Hassouneh et al. [7] also showed that if energy-efficient windows are used, flexibility in the choice of glazed area and orientation increases.

In the design of very well-insulated homes, the traditional guidelines of having larger windows to the south and smaller windows to the north, aimed at reducing heat loss on the north side while gaining as much solar heat as possible on the south, might therefore not be valid anymore. Instead, there is a need for a more nuanced window design that integrates both summer and winter conditions. Results from monitoring the thermal indoor environment in some of the first passive houses in Denmark [11] show overheating in some of the houses and the need to integrate natural ventilation and better solar control. A comparison also showed that houses designed with a more even window distribution (reduced area to the south and increased area in other orientations) were less subject to overheating.

To evaluate the selection of a particular window design and its influence on heating and cooling demand, attention should also be given to thermal zoning. Where the building parameters of different zones in a building vary, useful solar gains in each zone will also vary [12]. A study by O'Brien et al. [13] showed that thermal zoning has a significant effect not only on predicted energy performance and thermal comfort but also on optimal design selection, especially in solar homes because these are subjected to high levels of periodic solar heat gains in certain zones. O'Brien et al. suggest that a moderate level of detail should be applied to the issues of thermal zoning even in the early design stages. Yohanis et al. [12] suggest performing analysis of useful solar gains on a zone-by-zone basis to allow for differences in orientation, thermal mass, impact of adjacent zones, etc. However, in current building practice, single-family houses are often modelled as a single-zone. In Denmark, for instance, the program Be10, which is a one-zone model based on method 1 in EN13790, is used to document the theoretical energy use in buildings before approval of construction [14]. This approach requires less model input and less simulation time, but can result in underestimation of energy use.

It can be concluded from the above-mentioned research papers that selecting a good window design is very difficult. The purpose of this research was to provide clear guidance in the design of very well-insulated homes early in the design process by investigating in more detail the choice of window size, type and orientation, and their influence on energy consumption and thermal indoor environment for two window designs: a traditional design with large south-oriented windows and smaller windows to the north, and a window design with a more even window distribution. We also extended the investigation to include three energy performance scenarios defined by the Danish building code: the current energy performance requirements for standard buildings class 2010, and the requirements for low-energy buildings class 2015 and 2020 [15]. Furthermore, we modelled various zone configurations to illustrate their importance in relation to the prediction of energy performance and thermal indoor environment.

2. The building

The building considered is a representation of the size and layout of a typical Danish single-family house. The house consists of one storey and has a heated floor area of 163 m^2, see Figure 1.

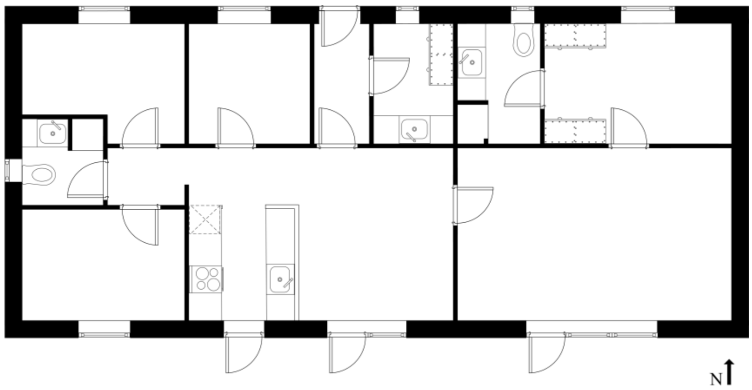

Figure 1: original plan of the building (adopted from [16])

In all scenarios, the external walls were modelled as brick and lightweight concrete cavity walls, the most common construction type in Danish single-family houses [17]. Starting with a design for the house that performs in accordance with the Danish building regulations today, upgrades in insulation thickness and window type were modelled to represent future energy performance requirements for low energy buildings in 2015 and 2020 [15]. The upgrades and thermal properties of walls, roof and floor are illustrated in Table 1.

Table 1 Insulation thickness and U-value of building envelope components.

	Component	Insulation thickness (mm)	U-value (W/m^{2}K)
2010	Wall	150	0.19
	Roof	200	0.16
	Floor	150	0.17
2015	Wall	200	0.14
	Roof	300	0.11
	Floor	200	0.13
2020	Wall	300	0.10
	Roof	400	0.08
	Floor	300	0.09

In the original design of the house, the glazing area is equal to around 15% of the internal floor area, which is recommended in the Danish building regulations [15] for sufficient lighting conditions in residential buildings constructed in accordance with 2020 energy performance requirements. The glazing area oriented towards south accounts for 63% (15m^2) of the total glazing area. The rest of the glazing area (9m^2) is mainly oriented towards the north. If we consider a reference case with even window distribution where the glazing area is equal to 15% of the heated floor area in each room, the glazing area facing south will be reduced by 14%, whereas the glazing area facing north will be increased by 25%.

A constant ventilation rate of 0.5 air changes per hour with heat recovery rates of 80, 85 and 90% has been considered for the 2010, 2015 and 2020 energy performance scenarios, respectively. Infiltration was set to 0.05 h^{-1} through the whole year. To ensure a good thermal indoor environment, venting was set to 3 h^{-1}, which corresponds to the maximum air flow rate possible for single-sided natural ventilation by automated opening of windows [18]. Previous research [19, 11] has shown that, in addition to venting, it is very important to integrate external solar shading early in the design to prevent the risk of overheating in very well-insulated homes, even though this is not usually done in northern Europe. Dynamically controlled external Venetian blinds were applied only to south/west-facing windows of the house, on the assumption that, with a high venting rate, thermal zones with a north/east orientation will have a good thermal indoor environment.

Design values for internal gains were implemented in accordance with standard practice in Denmark [18]. Internal gains were considered constant and were set to 3.5 W/m^2 for lighting and equipment and 1.5 W/m^2 for internal gains from people. User behaviour has a great influence on energy consumption in buildings [20-22], and especially in very well-insulated buildings. However, a building's user behaviour is often also the hardest thing to model and it was not part of this research to study the effect of user behaviour: but it definitely warrants further research.

2.1. Thermal zone configurations

As mentioned above, careful attention should be given to the assignment of thermal zones. Single-family houses are often modelled as a single zone, which ignores the effect of different solar gains and building parameters for rooms with different orientations in the house. For the purpose of investigating the influence of thermal zoning on the selection of window sizes and orientation, we studied 4 models with different thermal zone configurations: a single-zone model which reflects current modelling tendencies; a model with 2 zones where direct and non-direct solar gains are isolated from each other; a 6-zone model which represents newer buildings where it is possible to control different zones with a different thermostat; and a 11-zone model which corresponds to a more conservative modelling approach. An overview can be seen in Figure 2.

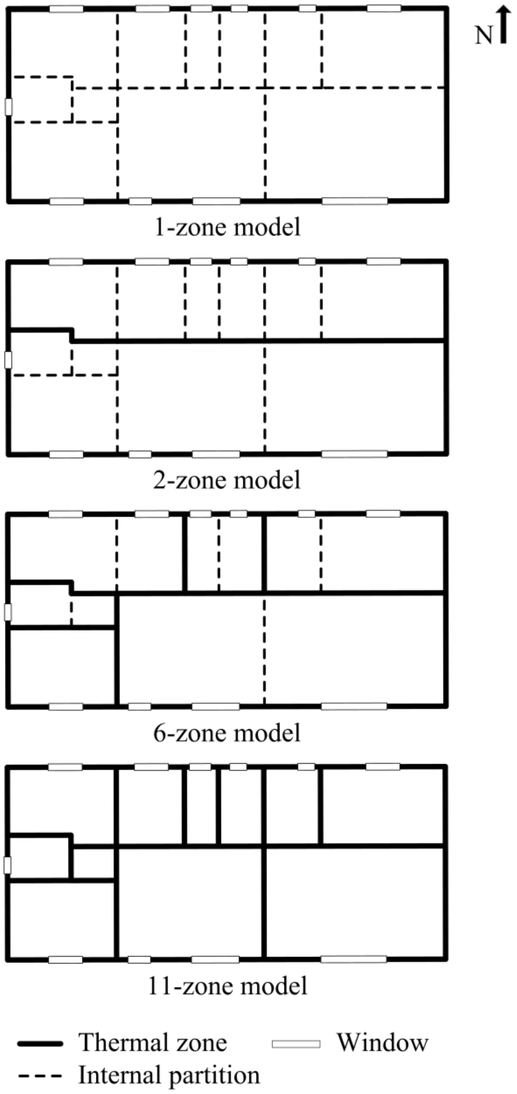

Figure 2: Illustration of thermal zone configurations

2.2. Parameters investigated

For each of the models with a different thermal zone configuration and energy performance requirement level, we investigated variations in window orientation, size and type.

- For a design with an even window distribution (same glazing-to-floor ratio in each room), 7 different window sizes were studied. The percentage of glazing-to-floor ratio varied from 10 to 50%. For variations on the original design with a larger glazing area to the south, window size varied from 10 to 30% of the floor area.
- The effect of orientation was investigated for south, north, east and west orientations by rotating the house as a whole with the original south façade turned towards the desired orientation.

- Six different types of glazing were studied, see Table 2. Type A was used as reference for the house constructed in accordance with 2010 energy performance requirements, whereas type B was used as reference for the house constructed in accordance with 2015 and 2020 energy performance requirements. Types C to F represent types A and B with solar-control coating applied. The use of glazing with solar-control coating is quite common in office buildings. It might be interesting to see if there is an application for glazing with solar-control coating in very well-insulated homes instead of using solar shading, which is usually more expensive. The window frame considered was the same throughout all investigations with a thermal transmittance of 0.9W/m^{2}K.

Table 2: The combined performance properties of the window types investigated.

Glazing type	Description	U_g (W/m^{2}K)	g_g (-)
Type A	Double glazing with one low-e coating	1.1	0.61
Type B	Triple glazing with two low e-coatings	0.7	0.48
Type C	Type A + solar-control coating	1.1	0.36
Type D	Type A + solar-control coating	1.1	0.28
Type E	Type B + solar-control coating	0.7	0.33
Type F	Type B + solar-control coating	0.7	0.24

3. Simulation method and assumptions

To investigate how energy use and thermal indoor environment are influenced by thermal zoning, insulation level, and the choice of window design and distribution, we used the parametric tool jEPlus [23, 24] and the building simulation tool EnergyPlus [25], which has been widely validated for its accuracy and consistency. EnergyPlus allows for hourly calculation of heating and cooling load and evaluation of thermal indoor environment based on detailed treatment of solar radiation [26]. jEPlus is designed as a parametric shell program for use with EnergyPlus.

The following assumptions were made in the EnergyPlus models:

- Transmitted solar radiation was calculated by using the ‘full interior and exterior with reflections’ algorithm. In this algorithm, the amount of beam radiation falling on each surface of the zone (including floor, walls and windows) is included in the calculation, instead of assuming that all transmitted beam radiation falls on the floor [26].
- The heating set point was fixed at 20^{o}C. Venting was set to start when zone temperatures exceed 24^{o}C. In accordance with standard modelling practice in Denmark, no cooling was implemented; instead overheating was evaluated in terms of the number of hours with temperatures above 26^{o}C.
- The ‘ideal loads air system’ was used to calculate heating loads, i.e. the power of the heating system was assumed infinite to reach the heating set point.
- The properties of the window types and solar shading were derived in WIS [27] and implemented in the EnergyPlus models.

- The external solar shading was modelled as a grey Venetian blind with a reflectance of 0.54 and a transmittance of 0.3. The shading was dynamically controlled to be activated outside the heating season when incident solar radiation on the windows exceeds 300W/m^2. When activated, the slat angle of the solar shading was adjusted to the cut-off angle to block direct sun. No glare control was implemented because it was assumed that internal curtains would be drawn by users.
- Weather data from the Danish Reference Year [28] was used for the calculations.
- For comparison of models representing the different zone configurations, equivalent mass needed to be maintained. We did this by modelling internal partitions as internal mass objects in EnergyPlus.

4. Results and discussion

First we discuss the simulation results obtained with the 6-zone model, and then we compare the models with different thermal zone configurations. Initially, hours with overheating are presented as a weighed sum of hours above 26^{o}C in each zone. However, to compare the thermal indoor environment of models with different thermal zone configurations, degree-hours with overheating above 26^{o}C have been used [13].

4.1. Orientation and window size

Figure 3 shows results for space heating demand for the different orientations and glazing-to-floor ratios of the house constructed in accordance with the various energy performance requirements for a design with an even window distribution (scen1) and for a more traditional window design with large glazing areas to the south (scen2). In each case, dynamic solar shading was used on the south/west-facing façade.

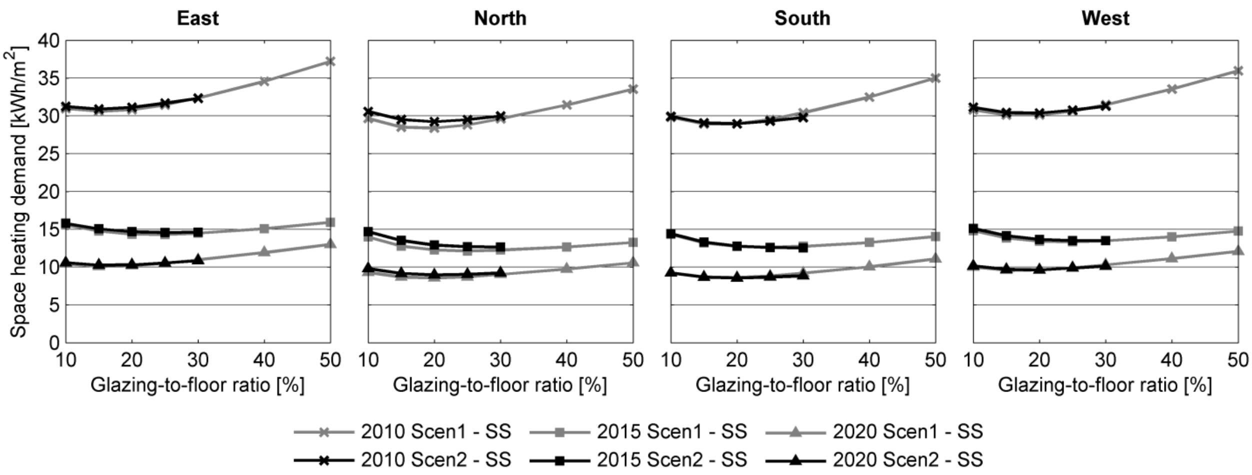

Figure 3: Space heating demand for different orientations and glazing-to-floor ratios.

Some general trends can be observed. The difference between a design with an even window distribution (scen1) and a more traditional window design with large glazing areas to the south (scen2) is minimal, although the latter performs slightly worse than the former when its large glazing area is oriented towards the north.

If we compare the various orientations in more detail, orienting the house towards north or south results in the lowest space heating demand, but there is generally not much difference in space heating demand for the different orientations. However, the house oriented towards the north orientation performs slightly better with large glazing-to-floor ratios than it does when oriented towards the south. Even for the house constructed in accordance with 2010 energy performance requirements, the effect of orientation on space heating demand is minimal. As previously indicated by Persson et al. [9], this shows that solar gains through south-facing windows have little influence on the reduction of space heating demand in well-insulated homes. On the contrary, well-insulated homes could be oriented differently and have a more even window distribution instead of the traditional design with large glazing areas to the south.

If we now look at the glazing-to-floor ratio, Figure 3 shows that although differences in space heating demand for different window sizes are small, there does seem to be a limit to benefits from increases in solar gains with increased glazing area. An optimal glazing-to-floor ratio of 20% can be found for the house when constructed in accordance with 2010 and 2020 energy performance requirements, and of 30% for the house constructed in accordance with 2015 energy performance requirements. And beyond the optimal window size, the increase in space heating demand is greater with increases in glazing area for the house constructed in accordance with 2010 energy performance requirements than for the house constructed in accordance with 2015 or 2020 energy performance requirements. This can be explained by the larger heat losses in the less well-insulated building envelope with larger glazing areas, even though a window type with higher g-value (type A) was used as reference. This confirms that there is a limit to the benefits from increases in solar gains through south-facing windows with increases in glazing area in well-insulated homes, and is also clearly illustrated in Figure 4: larger solar gains due to increases in glazing area in south-facing rooms do not contribute significantly to energy savings. However, the use of solar gains is still important to reduce space heating demand compared to north-facing rooms where space heating demand increases due to the increase in heat losses with larger glazing areas.

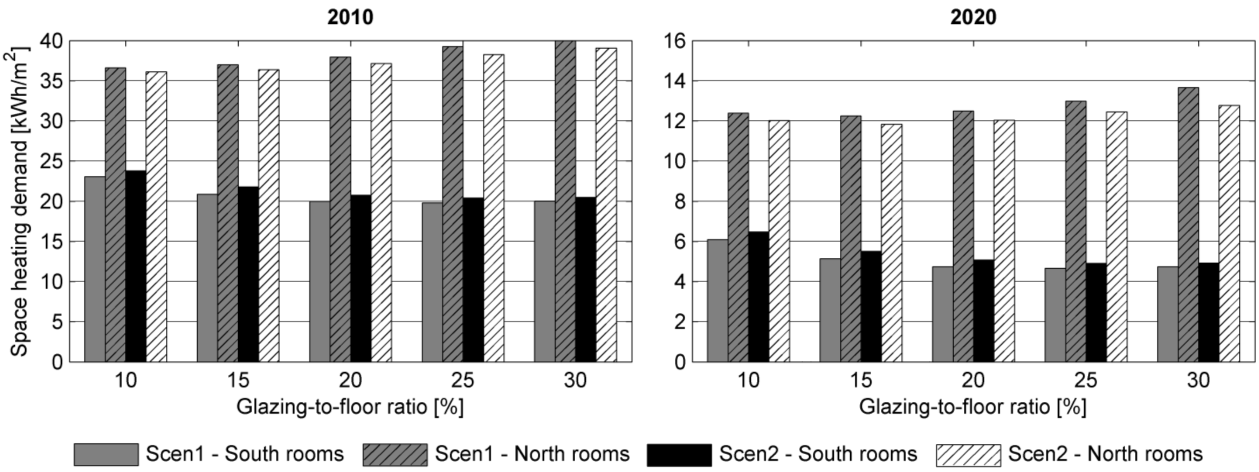

Figure 4: Comparison of space heating demand in north and south-facing rooms for different glazing-to-floor ratios with the south orientation of the house.

Figure 4 also allows more detailed comparison of a design with even window distribution and a traditional window design with large south-oriented windows. The use of larger south-oriented windows in the traditional window design results in slightly larger space heating demand in south-facing rooms than when an even window distribution is used. However, smaller north-oriented windows in the traditional window design mean lower heat losses and smaller space heating demand than the larger windows of the even window design are used, so the effects balance out at the level of the whole building.

Figure 5 shows results from evaluation of the thermal indoor environment for different orientations and glazing-to-floor ratios. Scenarios with and without dynamically controlled solar shading were considered.

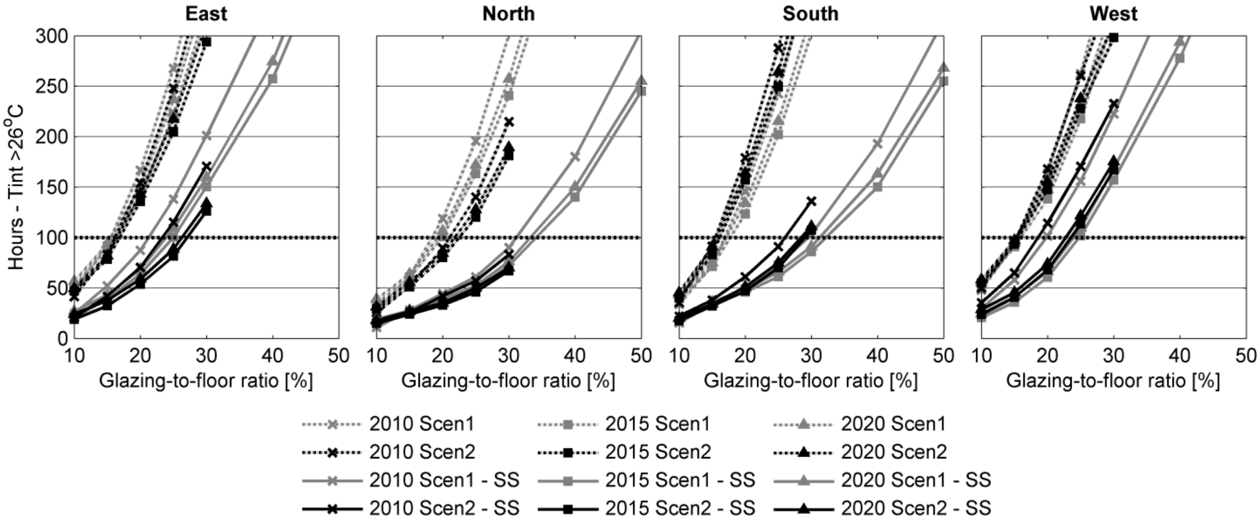

Figure 5: Hours with indoor temperature > 26°C for different orientations and glazing-to-floor ratios.

Not surprisingly, in all cases the least overheating occurs for north orientations. Overheating with a window design with even distribution is almost at the same level as for a traditional window design. For south orientations, the design with an even window distribution performs best. Differences in the risk of overheating between the design with an even window distribution and traditional window design increase with increasing glazing-to-floor ratio. Figure 5 also shows that for the house constructed in accordance with 2010 energy performance requirements, overheating is larger than for the house constructed in accordance with 2015 or 2020 energy performance requirements. This difference can again be explained by the difference in glazing type and indicates that careful attention should be given to avoid the risk of overheating in houses designed to 2010 energy performance requirements.

The Danish building code allows a maximum of 100 hours with temperatures above 26°C in critical rooms for buildings constructed in accordance with the 2020 energy performance requirements. As differences in space heating demand are rather small for different window sizes, especially for the house constructed in accordance with 2015 and 2020 requirements, the thermal indoor environment will limit the choice of window size. With dynamic solar shading on the south façade, a glazing area of up to 30% of the floor area can comfortably be chosen without exceeding the upper limits for acceptable thermal indoor environment for the design with even window distribution in a south orientation, whereas for the traditional window design a glazing area of around 25% is preferable. If we compare hours of overheating for east and west orientation, the application of dynamic controlled solar shading on west-oriented windows is not as effective as on south-oriented windows if solar shading is activated only when incident solar radiation on the windows exceeds $300W/m^2$. A more suitable activation set point should therefore be chosen to allow for larger glazing areas. Where no dynamic solar shading is present, the glazing area for south, east and west orientations is limited to around 15% for both window designs, whereas a glazing area of 20% is acceptable for north orientation for the traditional window design. Using dynamic solar shading on south/west façades allows for larger windows which provide improved views outside and use of daylight when the shading is open. However, if the expense of solar shading is to be avoided, the use of solar-control glazing might be an option. This is investigated in the following.

4.2. Window type

The effect of various window types on differences in space heating demand and peak heating load is shown in Figure 6 for the two window designs and for the house built in accordance with 2010 and 2020 energy performance requirements. The peak heating load was found as the maximum peak heating load among the different thermal zones to achieve the heating set point.

We chose the window types mainly to investigate whether solar-control coating could be used instead of solar shading. Results are only shown for south orientation of the house, but similar trends were seen for the other orientations. Where two window types are indicated, for example Type A+C in the figure, this represents the use of window type A for north-oriented windows and window type C for south-oriented windows. No investigations were conducted on using more energy-efficient windows or less energy-efficient windows for the house constructed in accordance with 2010 and 2020 requirements, respectively. To minimize heat losses, no alternative to energy-efficient windows should be used for the house constructed in accordance with 2020 requirements.

As expected, the results in Figure 6 show that the use of glazing with solar-control coating increases space heating demand compared to a design with dynamic controlled solar shading activated outside the heating season. However, the increase in space heating demand is small when glazing with solar-control coating is used only for south-facing windows. For both 2010 and 2020 requirements, glazing with moderate solar-control coating could be used without any noticeable difference in heating demand. This seems to indicate that there might be a g-value above which the extra solar gains through south-oriented windows do not help reduce space heating demand.

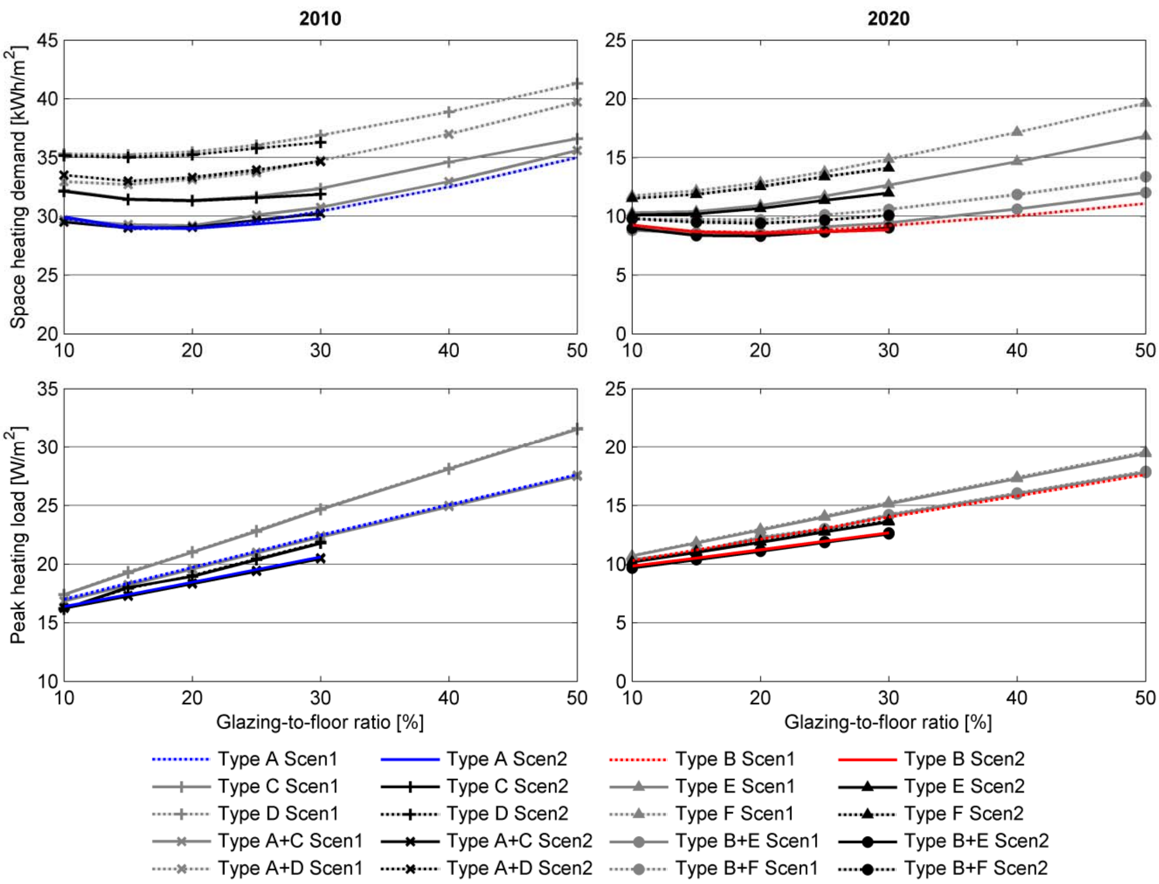

Figure 6: Space heating demand and peak heating load for different glazing types and glazing-to-floor ratios for the south orientation of the house.

With regard to glazing area, again an optimal glazing-to-floor ratio of 20% can be found for the house constructed in accordance with 2010 and 2020 energy performance requirements when using glazing with solar-control coating only for south-facing windows. When glazing with solar-control coating is used on both north and south windows, space heating demand increases with increases in glazing area and the optimal glazing area should be as small as possible allowing for daylight requirements.

In the selection of window type, not only space heating demand, but also peak heating load is of interest. Figure 6 shows that using glazing with solar-control coating only on south-facing windows gives the same peak heating load as for a design with dynamically controlled solar shading on south-facing windows. When glazing with solar-control coating is used on both south and north-facing windows, the peak heating load is higher. A window design with even distribution also has higher peak heating load than the traditional window design with large south-oriented glazing areas, but generally peak heating loads for the house constructed in accordance with 2020 requirements are in the range of 10-15W/m2 for a glazing-to-floor ratio of up to 30%. This could be relevant when used with low-temperature heating systems, such as self-regulating floor heating systems.

Figure 7 illustrates results for the thermal indoor environment for the different glazing types. They show that solar-control glazing can help to avoid overheating problems. For larger window sizes, the use of glazing with solar-control coating is to be preferred over the use of dynamically controlled external shading for the case investigated in this article. To comply with the requirements in the Danish building code [15], glazing types with severe solar-control coating (on south-facing windows or north and south-facing windows) are preferred and allow for a glazing-to-floor ratio of up to 25% for a traditional window design and up to and 30% for a design with even window distribution. If glazing with moderate solar control is used, the risk of overheating increases and window sizes of 20-25% are to be preferred.

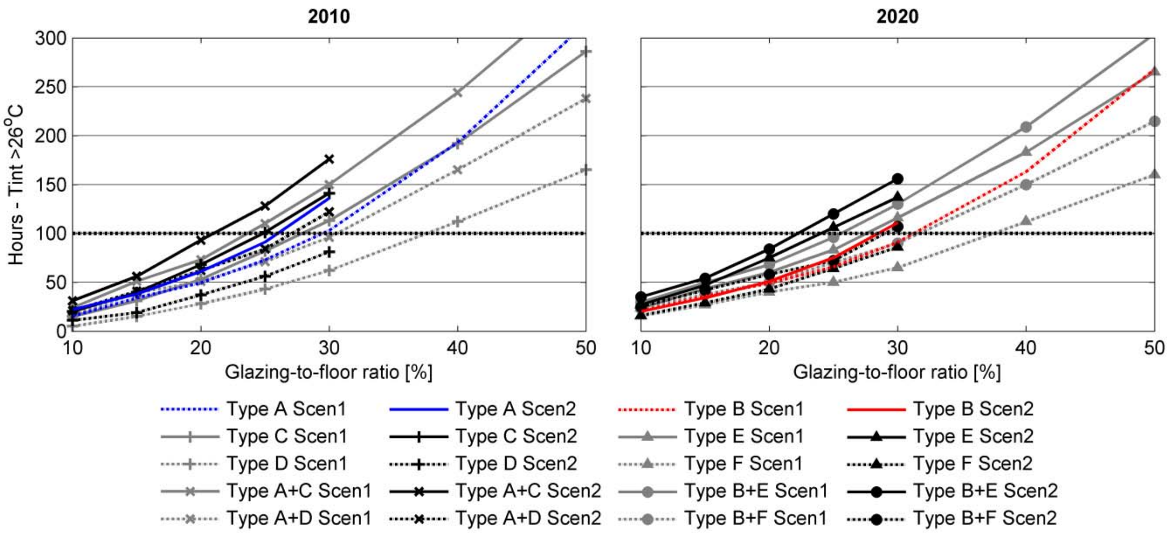

Figure 7: Hours with indoor temperature > 26oC for different glazing types and glazing-to-floor ratios for a south orientation of the house.

Glazing with solar-control coating can be used all year round instead of using dynamically controlled solar shading outside the heating season to prevent overheating, so the question remains of which is more cost-efficient and/or beneficial in use of daylight. Glazing with solar-control coating has a light transmittance which at maximum is twice the solar transmittance, which means that larger glazing areas are needed to allow the same use of daylight as when using clear glazing. Moreover, one should keep in mind that, depending on the type of solar-coating used, it can give a slight tint to the glass, which might be unwanted. On the other hand, external controlled solar shading is more expensive, requires more maintenance and blocks the view and daylight when closed. The decision on whether to use external solar shading or glazing with solar coating should be left to the building owner. In the end, it does not matter which option is used, as long as prevention of overheating is integrated in the design process from the beginning.

4.3. Influence of thermal zone configuration

Figure 8 gives a comparison between different thermal zone configurations for the design with even window distribution. Similar trends were observed for the traditional window design. The comparison is based on relative differences in heating demand and degree-hours of overheating in all the cases simulated, first using the single-zone model as reference for comparison with all other zone configurations and then using the 6-zone model as reference for comparison with the 2-zone and 11-zone model.

The results show that using a single-zone model underestimates the energy need for space heating because it assumes that air is well mixed in the house. The underestimation is greatest for the south orientation, where deviations in the range of 10-40% can be found. The underestimation also increases with increases in glazing area. Using the 6-zone model as reference, quite narrow variations can be found between using a 2-zone, 6-zone or 11-zone model. This is because zones with direct and non-direct solar gain have been isolated in all these models. However, using a 6-zone or 11-zone model results in slightly higher space heating demand because heating is more frequently used in the isolated non-direct solar gain zones for the 6-zone and 11-zone model than for the 2-zone model, see also Figure 9.

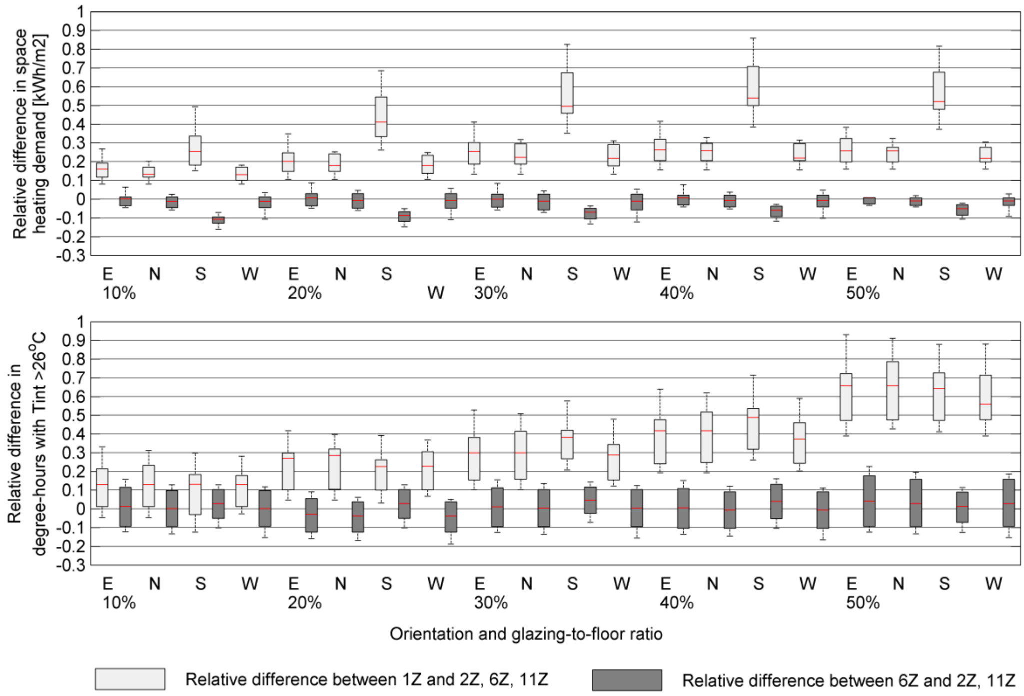

Figure 8: Comparison of space heating demand and degree-hours with indoor temperature > 26^{o}C for different thermal zone configurations with different glazing-to-floor ratios and orientations.

The results from the comparison of overheating (see Figure 8) show that, when a single-zone model is used, overheating is underestimated for all orientations. Overheating is more significant for thermal zone configurations with more zones because direct solar gains are isolated and thermal mass in the non-direct solar gain zones cannot be exploited. Differences in overheating also increase with increases in glazing area.

Figure 9 shows the influence of thermal zone configuration on optimal window size for space heating demand. Using a single-zone model, an optimal glazing-to-floor ratio of 30% can be found for the south orientation of the house constructed in accordance with 2020 energy performance requirements. This is 10% greater than the optimal glazing-to-floor ratio found with other thermal zone configurations. For other orientations, the optimal glazing-to-floor ratio when considering space heating demand is the same for all thermal zone configurations. Similarly, it was found that from an overheating point of view, glazing-to-floor ratios of up to 40% for south orientation can be chosen when using a single-zone model, whereas with other thermal zone configurations, a glazing-to-floor ratio of 30% can be chosen. Using a single-zone model, differences between a design with even window distribution and a traditional window design are also greater than when using more thermal zones. Differences in space heating demand for different orientations are also smaller when using more thermal zones, as a result of isolating zones with direct and non-direct solar gains.

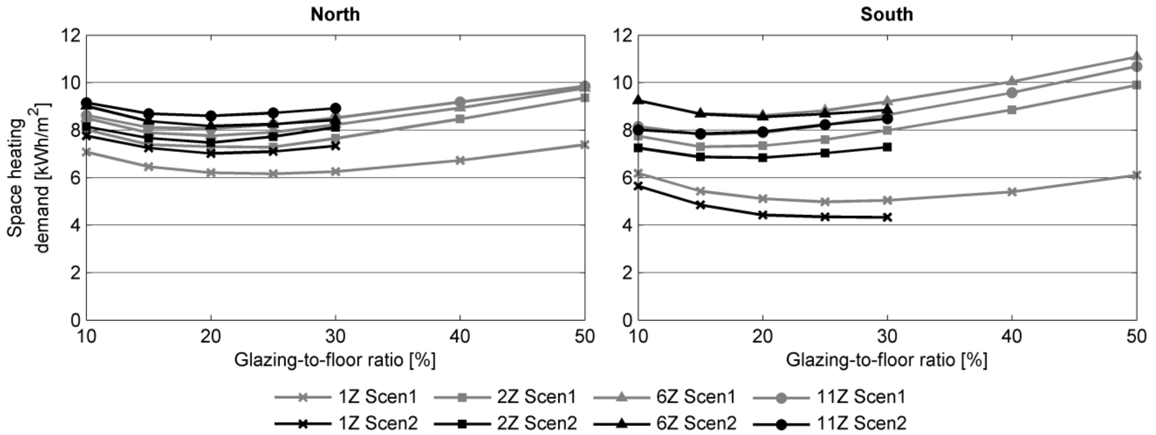

Figure 9: Illustration of space heating demand for different thermal zone configurations with different glazing-to-floor ratios and orientations for the house constructed in accordance with 2020 energy performance requirements.

This shows that with regard to thermal zone configuration, the most important thing is to ensure a difference in zones with direct and non-direct gains. For better characterisation of space heating demand and the risk of overheating, however, it is recommended that models with more thermal zones should be used, though one should weigh the cost of extra time spent to build up the model against the gains in accuracy.

As is usual in the early design phases, internal gains were assumed to be a constant of 5W/m2 for the all thermal zones in the different zone configuration models. It is expected that the influence of thermal zoning would be even greater when if the different internal gains in rooms depending their usage were taken into account. Interzonal airflow has also not been considered when comparing models with different thermal zone configurations. As O'Brien et al. [13] showed, this can have great influence on the prediction of energy use and the thermal indoor environment, but is most relevant for buildings using forced air systems.

5. Conclusion

This article presents research on how space heating demand and thermal indoor environment are influenced by window size, type and orientation. From direct comparison of a traditional window design with large south-oriented windows and a design with an even window distribution for a typical Danish single-family house, it has been demonstrated that the effect of orientation and south-facing window size has decreased in the well-insulated homes of today and those that will be built in accordance with future energy performance requirements, so that making use of solar gains through south-oriented windows is not as important as is traditionally believed. This contrasts with current building design guidelines, which seek to take advantage of the free solar gains from large south-oriented windows. In fact, we have shown that increasing south-facing window size does not result in reductions in space heating demand. By comparing the effect of glazing with different solar-control coatings, we have also found that there might be a g-value above which the extra solar gains through south-oriented windows no longer help reduce space heating demand. It then becomes important to use solar shading or glazing with solar-control coating as a cheaper alternative to reduce overheating.

Maximum glazing area from an overheating perspective was found to be 30% of the floor area with an even window design. When a more traditional design is used, a maximum of 25% glazing-to-floor ratio is recommended in south-oriented homes. Optimal window sizes found from the space heating demand perspective are smaller, but differences in space heating demand for optimal window sizes and larger window sizes are very small and the building owner should decide whether or not he wants larger glazing areas to allow for more daylight. Furthermore, because the orientation and size of windows is of less importance in well-insulated homes, it should be possible to choose windows on the basis of the use of the rooms behind the façade and in accordance with the wishes of the building owner within the limits for overheating. In other words, windows can be positioned in the façade with considerable architectural freedom, without sacrificing the indoor environment or causing a significant increase in the energy required for heating. However, we do recommend an even distribution of the glazing-to-floor ratio, because this generally provides an improved thermal indoor environment and will ensure a better daylight level especially in north-oriented rooms. The aspect of daylight was not part of our investigation, but this will be the topic for further research.

With regard to thermal zoning, we have demonstrated that using a single-zone model underestimates both the energy need for space heating and the risk of overheating. This also impacts on the optimal window size. Modelling a building using a single zone increases the optimal window size because it assumes that solar heated air is well mixed in the house. During the early stages of the design process, it is important to be able to predict the relative performance of energy needed for space heating and to identify the risk of overheating because this is where the most important decisions about window size are made. With regard to thermal zone configuration, a difference in zones with direct and non-direct gain zones is needed. For better characterisation of risk of overheating (and space heating demand), however, it is recommended that models with more thermal zones should be used, but one should weigh the cost of extra time spent to build up the model against the gains in accuracy.

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Paper II

Impact of window design on energy, daylight and thermal indoor environment in a nearly zero-energy house.

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IMPACT OF WINDOW DESIGN ON ENERGY, DAYLIGHT AND THERMAL ENVIRONMENT IN NEARLY ZERO-ENERGY HOUSES

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Abstract

Windows have considerable effect on energy consumption and indoor environment. Appropriate window solutions are decisive for the design of 'nearly zero-energy' buildings with healthy indoor environment and they need careful consideration. This paper provides insight into the relationship between glazing-to-floor ratio, orientation and glazing properties of side-lit windows for various room geometries representing Danish 'nearly zero-energy' houses. The effect of these parameters on space heating demand, daylight and thermal environment is evaluated by means of EnergyPlus and DAYSIM and presented in diagrams illustrating how combinations of design parameters with minimum space heating demand can be selected within a space of solutions defined by targets for minimum daylight and overheating. The results show that there is an upper limit for utilisation of solar gains in south-oriented rooms and that the choice of g-value from perspective of space heating demand corresponds well with the g-value for prevention of overheating by permanent solar shading. Furthermore, in north- and south-oriented rooms, the use of large glazing-to-floor ratios is a disadvantage in terms of space heating demand at high U-values but an advantage at very low U-values. With regard to geometry, either daylight or thermal comfort must be compromised in deep or narrow south-oriented rooms.

Keywords: nearly zero-energy buildings, fenestration, indoor environment, daylight availability, glazing properties, geometry factors, median daylight factor method.

1 Introduction

As part of European energy strategy and policy for reducing the use of fossil fuels, all new buildings are required to have a ‘nearly zero’ energy consumption in 2020 [1]. This creates a strong need for research in cost-effective technology and solutions that will help meet these ambitious energy reductions without compromising on daylight conditions and indoor climate. It is well-known that windows have a considerable effect on both energy consumption and indoor environment. For example, where large windows allow for more daylight in a space, they might also result in visual discomfort and excessive heat gains or losses which affect the energy needed for heating or cooling and the thermal indoor environment. So it is important to find a balance between daylight availability, thermal comfort and energy consumption if we are to achieve both the goal of a ‘nearly zero’ energy use and buildings with a healthy and comfortable indoor environment. There have been many studies on window design with regard to energy use for heating, cooling and lighting in office buildings. Studies carried out by Susorova et al. [2] and Ghisi and Tinker [3] focused on the effect of room geometry, window size and orientation on energy use for heating, cooling and lighting for office buildings in various climate zones. A study by Lee et al. [4] examined the effect of window-to-wall ratios, orientation, U-value, g-value and visual transmittance to find optimal window designs for office buildings in 5 typical climate zones in Asia. Similarly, Motuziene and Juodis [5] investigated the effect of window-to-wall ratios, window orientation and glazing type on the total building energy use for an office building in the cool climate zone of Lithuania, while a study conducted by Ko [6], explored ways of optimising daylighting and energy savings by performing energy simulations to find the best combination of window area, U-value, g-value and light transmittance for office buildings in six different climates in the U.S.

Due to the less predictable usage and occupancy in residential buildings, where the majority of the occupancy, for example, might be found outside the daylight hours, the link between energy use, thermal environment and daylighting is less obvious in residential buildings than in commercial buildings. Furthermore, while in office buildings most energy is used for cooling and lighting, in residential buildings there has been a historical focus on reducing the energy needed for heating. These might be reasons why, the topic of the integrated evaluation of window design and its combined effect on heating, cooling and lighting has been less explored in residential buildings. A number of studies on the topic of lighting in residential buildings have evaluated daylight availability and the potential for savings in artificial lighting with various geometries and window sizes [7-9]. Studies on reducing the heating and cooling demand in residential buildings have considered the influence of window orientation, size and glazing type and suggested that south-facing window size is important for reducing heating demand [10-13]. However, a study by Persson et al. [14] on the performance of passive houses in Sweden has shown that window size is not that important any more for the reduction of heating demand. In well-insulated residential buildings, the focus should be on reducing the risk of overheating. Recently, there has been renewed attention on the thermal indoor environment and potential non-visual effects of daylighting in residential buildings [15] as part of a movement towards sustainable buildings with a focus on user well-being [16]. ‘Active houses’ [16] should be designed, for example, so that they allow for optimal daylight and attractive views to the outside while ensuring a good thermal indoor environment and low energy consumption without having negative impact on the environment. Following the Active house specifications [17], a house called 'Home for life' was designed and constructed in Denmark as part of the Model Home 2020 project, which has the aim of developing climate-neutral buildings with a high level of livability [18]. The house has a window-to-floor ratio of 40% to achieve an average daylight factor of 5%. This is about twice the window-to-floor area usually used in single-family houses. Even so, the overall thermal indoor environment is good, due to the special attention given to solar control using dynamic solar shading and ventilative cooling by natural stack ventilation through the use of roof windows [19]. Another example is the design of a Danish passive house [20] in which the glazing area was selected to provide a daylight factor of 2% all the way to the back of primary rooms. Here, however, there were problems with overheating because no solar control of any kind was provided [21].

We believe that the establishment of cost-effective and successful window solutions in 'nearly zero-energy' buildings requires more knowledge about the link between various window design parameters and their combined effect on space heating demand, daylight availability and thermal indoor environment for rooms with various geometries. In this paper we wish to contribute to this knowledge by studying the effect of glazing-to-floor ratio, orientation, and glazing properties such as U-value, g-value and light transmittance in rooms with various geometries representing Danish 'nearly zero-energy' single-family houses. The results are presented in terms of diagrams, exemplifying an approach by which window solutions with minimum space heating demand can be chosen within a space of solutions defined by targets considering minimum daylight availability and overheating.

2 Methodology

2.1 Simulation process and model description

Daylight availability was computed independently from energy consumption and thermal indoor environment. For the calculation of energy consumption and thermal environment, the building simulation tool EnergyPlus [22] was used in combination with the tool jEPlus [23, 24], which is a parametric shell program designed for use with EnergyPlus. EnergyPlus has been widely validated and is an acknowledged simulation tool that uses the heat balance model to predict thermal loads in buildings. Analyses with regard to daylight were carried out using the RADIANCE-based daylighting analysis tool DAYSIM [25].

2.1.1 Room geometry

To study the relationships between window size, orientation, U-value, g-value and visual light transmittance, the investigations were made at room level. This made it possible to investigate how window size, orientation and geometry affect the performance in a transparent way. A total of 9 different room dimensions with varying width-to-depth ratios were used, see Table 1.

Rooms were modelled with ceiling, floor and one façade exposed to the outside climate. Corner rooms were not considered and no external obstructions were taken into account. Room height was set to 2.5m and a wall thickness of 0.5m was used.

Table 1: Room dimensions and width-to-depth ratio for each room geometry.

	2:1		1.5:1		1:1		1:1.5		1:2	
	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)	W (m)	D (m)
Large rooms	8	4	6	4			4	6	4	8
Base case					4	4				
Small rooms	5.3	2.7	4	2.7			2.7	4	2.7	5.3

2.1.2 Building specifications

Construction and building system properties for the various room geometries were selected to allow a maximum target space heating demand of 13 kWh/m^2 when space heating demand in north and south-oriented rooms is averaged at the level of the whole building and extra heat losses from corner rooms are included. Table 2 contains input data on construction, building system properties, and internal loads for the simulation model. The heating set-point and design values for internal gains were chosen in accordance with standard practice in Denmark [26]. Heating power to achieve the heating set point was assumed infinite by using the ideal loads air system in EnergyPlus [27]. Infiltration was set to 0.05 h^{-1} for the whole year, while venting was set to 3 h^{-1}. This corresponds to the maximum air flow rate possible for single-sided ventilation using automatic opening of windows [26]. To ensure a good thermal indoor environment, solar protection should be integrated early in the design [21, 28], in addition to venting. Recent findings [29] have indicated that the importance of a high g-value for reducing space heating demand for south-oriented rooms in ‘nearly zero-energy’ buildings is limited even in the Danish climate, which makes the cost-efficiency of dynamic shading solutions debatable. Therefore, in this research work, we considered g-value to reflect the use of permanent solar shadings instead of using dynamic shading solutions. Furthermore, we assumed that users can draw curtains to control glare, or adapt to glare by moving around in the space.

Table 2: Input values defining the thermal simulation model with respect to construction properties, and system and internal loads.

Construction properties	
U-value wall[1)]	0.10 W/m^{2}K
U-value roof[1)]	0.08 W/m^{2}K
U-value floor[1)]	0.09 W/m^{2}K
System and internal loads	
Heating set point	20°C
Venting set point	23°C
Infiltration rate	0.05 h^{-1}
Venting rate (maximum)	3 h^{-1}
Mechanical ventilation rate	0.6 h^{-1}
Efficiency of heat recovery	0.9
Internal gains from people	1.5 W/m^2
Internal gains from equipment and lighting	3.5 W/m^2

1) Includes linear heat losses

For daylight calculations, a diffuse reflectance of 70% was assumed for walls and ceiling and a reflectance of 30% for floors.

2.1.3 Parameter variations

Glazing-to-floor ratio, orientation, and glazing properties such as U-value, g-value and visual transmittance were varied as indicated in Table 3 for each of the room geometries. The window frame considered for the investigations has a thermal transmittance of 0.9W/m^{2}K and a width of 5cm, which was kept the same for all investigations.

Table 3: Variables used for parameter analyses.

Parameter	Variable
Orientation	N/S
Glazing-to-floor ratio[1)] (%)	10/15/20[2)]/25[3)]/30/35
Glazing U-value (W/m^{2}K)	0.3/0.5/0.7/0.9
Glazing g-value (-)	0.1/0.2/0.3/0.4/0.5/0.6/0.7
Light transmittance (-)	0.3/0.4/0.5/0.6/0.7

1) Based on internal floor area.
2) Glazing-to-floor ratios greater than 20% were not investigated for the room with geometry 4m x 8m.
3) Glazing-to-floor ratios greater than 25% were not investigated for the room with geometry 4m x 6m.

For the different glazing-to-floor ratios, the glazing height was kept constant at 1.5m while the glazing width was varied. Windows were placed as high in the façade as possible from an optimal daylight point of view. Depending on the room geometry, rooms were side-lit by 1 to 4 windows. A consistent relationship between the off-set from side walls and off-set between windows was used to ensure an optimal daylight distribution. Figure 1 illustrates the variation in glazing-to-floor ratio for a 4m x 4m room.

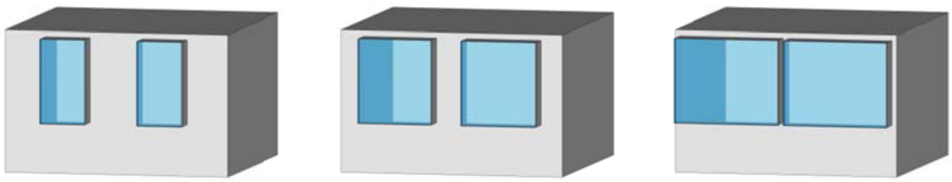

Figure 1: Illustration of glazing-to-floor-ratio for a 4m x 4m room. From left to right: Glazing-to-floor ratio of 15%, 25% and 35%.

2.1.4 Weather data

The study considered rooms with various geometries for single-family houses located in Copenhagen, Denmark. This location in the northern part of continental Europe (latitude 55.6° and longitude -12.7°) represents a temperate coastal climate with rather small temperature differences between summer and winter and low to medium access to daylight and solar radiation on an annual basis. Weather data from the Danish Reference Year [30] was used for the calculations.

2.2 Evaluation criteria

Since the tradition for mechanical space cooling is limited in Denmark due to the climate, we evaluated energy consumption based on the space heating demand alone, while the thermal comfort was considered a boundary condition restricting the allowable space of window solutions. We evaluated thermal comfort based on the Danish building code requirements for nearly-zero residential buildings [31], which state that, to avoid overheating, no more than 100 hours where the operative temperature exceeds 26 degrees should be allowed. The methodology and targets for the evaluation of daylight in residential buildings are less clearly defined. For offices, a daylight factor of 2% is required in the working plane, but for nearly-zero energy residential buildings, the Danish building code only requires a minimum glazing-to-floor ratio of 15% in primary rooms when side-lit windows with a light transmittance of 0.75 are used [31]. If the light transmittance is lower, the glazing-to-floor ratio should be increased proportionally. Moreover, electricity consumption for artificial lighting is not included in the target for primary energy consumption in residential buildings. For these reasons and the less obvious usage and occupancy in residential buildings where most of the occupancy often occurs outside the daylight hours, daylight was evaluated as an independent performance parameter, rather than expressed in terms of a reduction in energy used for artificial lighting. Provided that rooms are designed for a high daylight performance with regard to comfort and health, we considered the potential electricity savings for artificial lighting a question of control systems and the usage of the building, rather than of window design. In the following, we present a target and methodology for the evaluation of daylight.

2.2.1 Target and methodology for evaluation of daylight availability

We selected target and methodology for the evaluation of daylight availability with reference to the on-going discussions on how European daylight standards can be upgraded in a way that approaches climate-based daylight modelling (CBDM), which provides daylight predictions under realistic sun and sky conditions based on available weather data [32]. Over the last decade, research in the field of daylighting has discussed the shortcomings of the daylight factor method [32, 33]. The daylight factor is calculated under standard CIE overcast sky conditions, so variations in daylight over time for different climates, locations and building orientations are not considered.

Recently, Mardaljevic and Christoffersen [34] suggested the use of a slight modification to the daylight factor method that creates connectivity to the diffuse daylight access at a specific location and provides a transition between the current practice of using the daylight factor method and the use of CBDM. On the assumption that the diffuse daylight access follows the same graduation in brightness as the CIE overcast sky model, a target daylight factor (DF_{target}) for various locations can be derived based on the target for median illuminance indoors (E_{target}) and the diffuse median illuminance available outdoors ($E_{median\ diffuse}$) during daylight hours:

$$DF_{TARGET} = \frac{E_{TARGET}}{E_{MEDIAN\ DIFFUSE}} \tag{1}$$

with $E_{MEDIAN\ DIFFUSE}$ calculated as the cumulative availability of diffuse illuminance from standardized climate files during daylight hours and with daylight hours defined as the hours from sunrise to sunset (solar altitude ≥ 0°).

When E_{TARGET} is set to 300 lux, the target daylight factor in Copenhagen is calculated to 2.11% [34]. Mardaljevic and Christoffersen argue that a target of 300 lux of natural indoor illumination is considered adequate by most building users [34]. Furthermore, they suggest that the target of 300 lux should be achieved in side-lit rooms across 50% of the work plane. As the median of diffuse illuminance is used, this means that, for half of the daylight hours in a year, half of the surface of the horizontal work plane receives 300 lux or more daylight. In this study, we used the methodology and target specified above for the evaluation of available daylight. This provides information about the spatial distribution in the room (which the average daylight factor does not) and ensures at the same time that daylight in rooms is not only evaluated based on their predicted occupied period due to the choice of the daylight hours as the evaluation period. However, this is not a fully climate-based approach and cannot be used as a measure for equal daylight availability for south- and north-oriented rooms over time under realistic sky conditions. On the other hand, because the methodology for evaluation of daylight is based on overcast sky conditions, it does ensure that a sensor-point that reaches the target daylight factor (DF target) will receive a minimum of 300 lux in 50% of the daylight hours on an annual basis. The spatial distribution of the target for daylight was evaluated for a grid of sensor points with a mask width of 0.2 distributed over the surface of the horizontal work plane at 0.85m above floor level.

2.3 Coupling between daylight availability and thermal environment

The aspects of space heating demand, daylight and thermal indoor environment were evaluated separately. By combining results for heating demand, thermal indoor environment and daylight into the same graphical illustration, we can obtain useful information about the relationships between these aspects. For each room geometry investigated, space heating demand was plotted in a contour plot as a function of glazing-to-floor ratio and g-value for north and south orientations separately. The combinations of glazing-to-floor ratio and g-value at which indoor temperatures were above 26°C for more than 100 hours were plotted as the boundary indicating overheating on the contour plot, see Figure 2.

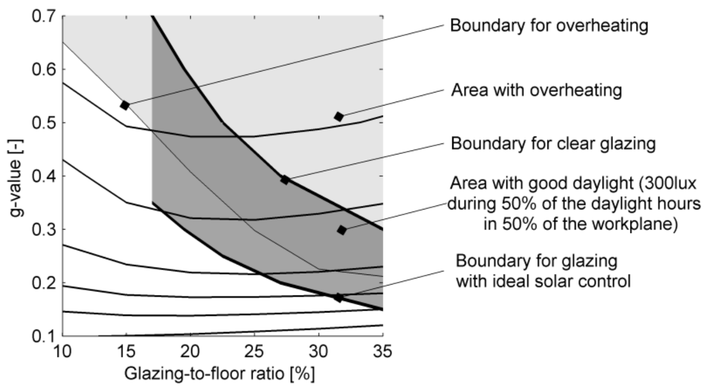

Figure 2: Conceptual illustration of contour plot of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target.

The link between the energy needed for space heating and daylight was established through the relationship between g-value and light transmittance. This relationship, also known as the ‘daylighting efficiency’ of glazing, varies for different glazing products. However, due to physical limitations, light transmittance is at maximum twice the solar transmittance (daylight efficiency 2). This characterizes glazings with an ideal solar control and serves as a lower limit to illustrate daylight availability. The upper limit is set to represent a clear glazing that is advantageous in situations where a large amount of solar gain is beneficial. This relationship is difficult to predict in a way that reflects reality, so we chose to define this boundary as the case where the light transmittance equals the solar transmittance (daylight efficiency 1). The minimum window area that is needed for different light transmittances can then be illustrated as an area ranging from a solar glazing with a g-value as low as possible for a given light transmittance to a clear glazing with g-value as high as possible for a given light transmittance. Existing products on the market can be found within this range of different daylight efficiencies. So the space of solutions defined by the boundaries for daylight and thermal indoor environment can be used to find a window design with the lowest space heating demand.

3 Results

In the following, we first discuss the results for the base case, a room with dimensions of 4m by 4m. Afterwards, we compare and discuss results for the other room geometries.

3.1 Space heating demand, overheating and daylight in a 4m x 4m room

Before discussing the full space of solutions defined by the targets for daylight and thermal indoor environment, we discuss the interrelationship between the glazing U-value, g-value and glazing-to-floor ratio focusing on some important tendencies that are related to their effect on space heating demand and overheating.

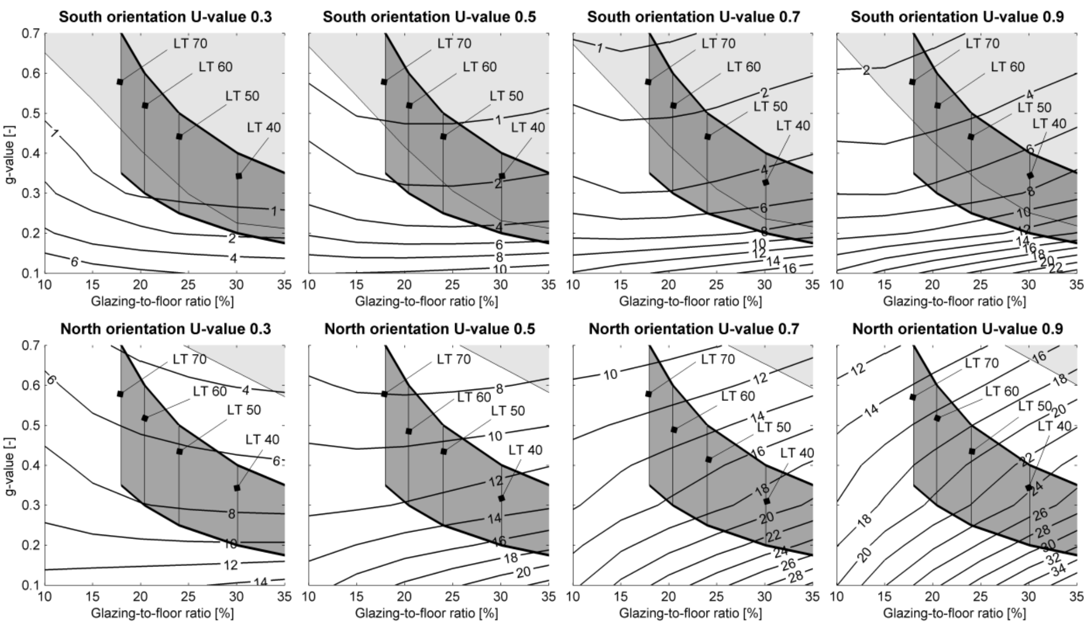

Figure 3: Contour plot of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for a room with dimensions of 4m x 4m and for different glazing U-values.

3.1.1 Effect of U-value, g-value and glazing-to-floor ratio on space heating demand and overheating in well-insulated buildings

As can be seen in Figure 3, variation in U-value has only marginal effect on thermal environment for the range of variables considered. On the other hand, the choice of g-value and glazing-to-floor ratio is highly decisive for whether overheating can be avoided, and for south-oriented rooms, the prevention of overheating will determine the final selection of g-value for the various glazing-to-floor ratios. A second observation is that sufficient access to solar gains is highly beneficial for reducing space heating demand. However, in south-oriented rooms, these benefits tend to stagnate after a certain access to solar gains, which indicates that there is an upper limit for the amount of solar gain that can be utilised efficiently in well-insulated rooms facing south. The access to solar gains is determined by the combination of g-value and glazing-to-floor ratio, but since the glazing-to-floor ratio determines both solar gains and heat losses, the point of stagnation is most clearly seen when studying the g-value. The ability to utilise solar gains varies across U-values, but for U-values of 0.5 W/m^{2}K and below a relatively pronounced stagnation can be observed at g-values as low as 0.3–0.4. For the U-values 0.7–0.9 W/m^{2}K, the stagnation occurs at slightly higher g-values, but for g-values above 0.5, increasing the g-value further will reduce space heating demand by less than 1 kWh/m^2. In north-oriented rooms, where space heating demand is higher, the benefits of high g-values for reducing space heating demand decrease with lower U-values and with higher g-values, but in general the importance of a high g-value remains significant for the whole range of variables investigated. Furthermore, we can observe that the effect of glazing-to-floor ratio on the reduction of space heating demand has an optimum at glazing-to-floor ratios of approximately 15–20%. In south-oriented rooms, glazing-to-floor ratios below 15–20% generally have a positive effect on space heating demand for all U-values, ranging from relatively pronounced at the lowest U-value to nearly constant at the highest U-value. Once the optimum glazing-to-floor ratio is reached, larger glazing-to-floor ratios become a disadvantage in terms of space heating demand for U-values above 0.5 W/m^{2}K, while for U-values below 0.5 W/m^{2}K large glazing-to-floor ratios remain an advantage, although their effect on the reduction of space heating demand starts to stagnate. The U-value of 0.5 W/m^{2}K seems to be the turning point at which the effect of increased glazing-to floor ratio changes so slowly from positive to negative that the effect of glazing-to-floor ratio on space heating demand remains nearly constant for all ratios. Similar tendencies can be found for the lower U-values in north-oriented rooms. When considering the U-value of 0.3 W/m^{2}K, it can actually be seen that while the positive effect of increased glazing-to-floor ratio on the reduction of space heating demand stagnates significantly in south-oriented rooms due to the limited amount of solar gains that can be utilised, the positive effect of increased glazing-to-floor ratios remains relatively pronounced in north-oriented rooms.

For higher U-values, large glazing-to-floor ratios are a disadvantage from the perspective of space heating demand for any glazing-to-floor ratio in north-oriented rooms. This indicates that the amount of solar gains that can be utilised in well-insulated buildings can only outweigh the additional heat losses that occur with larger glazing-to-floor ratios when extremely low U-values are used. Altogether, the observations show that high g-values and large glazing-to-floor ratios in south-oriented rooms are less important than traditionally believed for the design of ‘nearly zero-energy’ residential buildings. This is in contrast to current practice in Denmark, where high g-values are favoured by the energy rating system for windows and large glazing-to-floor ratios in south-facing façades are often recommended.

3.1.2 Space of solutions

The range of solutions for which both thermal comfort and daylight conditions are satisfactory (Figure 3) is considerably larger for rooms oriented towards the north than for rooms oriented towards the south. For south-oriented rooms, only glazing products with close to ideal daylight efficiency (see Section 2.3) can allow enough daylight without exceeding the limits for overheating. As long as the glazing-to-floor ratio is carefully dimensioned based on the daylight target and combined with appropriate g-values to avoid overheating, glazing products with any of the light transmittances indicated in Figure 3 can be chosen. The range of available g-values is slightly larger for high light transmittances than for low light transmittances, while the potential savings in space heating demand by choosing the highest g-values over the lowest g-value in the range increases slightly when going towards the lower light transmittances. These savings must, however, be seen in the light of the increased risk of overheating and compared with the benefits that could be achieved by lowering the U-values. Furthermore, a high light transmittance will allow the use of smaller glazing-to-floor ratios, which could be an advantage in cases where less glazing is desirable due to cost and will also allow for the lowest possible space heating demand for high U-values. If larger window areas are preferred, the narrow space of solutions in south-oriented rooms due to overheating will require that increased glazing-to-floor ratios must be combined with a reduction in g-value in most cases. This combined effect of large glazing-to-floor ratio and low g-values does not noticeably influence space heating demand when very low U-values are used, but it does have a significant effect when high U-values are used. In terms of space heating demand, the consequence of using a glazing with g-value of 0.2 and a glazing-to-floor ratio of 35% (light transmittance less than 0.4) compared to a glazing with g-value of 0.45 and a glazing-to-floor ratio of 17.5% (light transmittance of 0.7) is approximately 10kWh/m^2 when using a U-value of 0.9W/m^{2}K. If overheating was not to be considered, the same change would correspond to an increase in space heating demand of as much as 3kWh/m^2. In conclusion, in south-oriented rooms, glazing products with low U-values and high light transmittances generally provide a better fit between the maximum allowable g-values from the perspective of overheating and the g-values at which the effect on space heating demand starts to stagnate.

In north-oriented rooms, clear glazing products (i.e. g-values that are as equal to the light transmittance as possible) can be used because the risk of overheating is limited, and they are preferable in order to reduce space heating demand. Savings achievable with clear glazing products are also greater in north-oriented rooms than in south-oriented rooms. However, the maximum achievable g-values depend on technical considerations that are especially important to take into account when considering the lowest U-values. As in south-oriented rooms, glazing-to-floor ratios in north-oriented rooms can be relatively freely chosen in terms of space heating demand when using low U-values, but since very little overheating occurs in north-oriented rooms, high g-values can be used irrespective of the glazing-to-floor ratio. This means that when large glazing-to-floor ratios with a glazing U-value of 0.3 W/m^{2}K are used, north-oriented rooms can take more advantage of the reduction of space heating demand than south-oriented rooms. Furthermore, for high U-values, the negative effect on space heating demand of using very large-glazing-to-floor ratios is less pronounced in north-oriented rooms than in south-oriented rooms. This also implies that by selecting appropriate glazing solutions for each orientation the difference in space heating demand between north- and south-oriented rooms can be reduced.

3.2 Daylight achievement and the space of solutions for different geometries

We now discuss how the space of solutions changes for rooms with different geometries. As an example, Figure 4 illustrates the space of solutions for two different room sizes with width-to-depth ratios of 1:1.5 and 1.5:1 for a glazing U-value of 0.5 W/m^{2}K. The same trends can, however, also be extended to geometries with width-to-depth ratios of 1:2 and 2:1 and the other glazing U-values investigated in this paper.

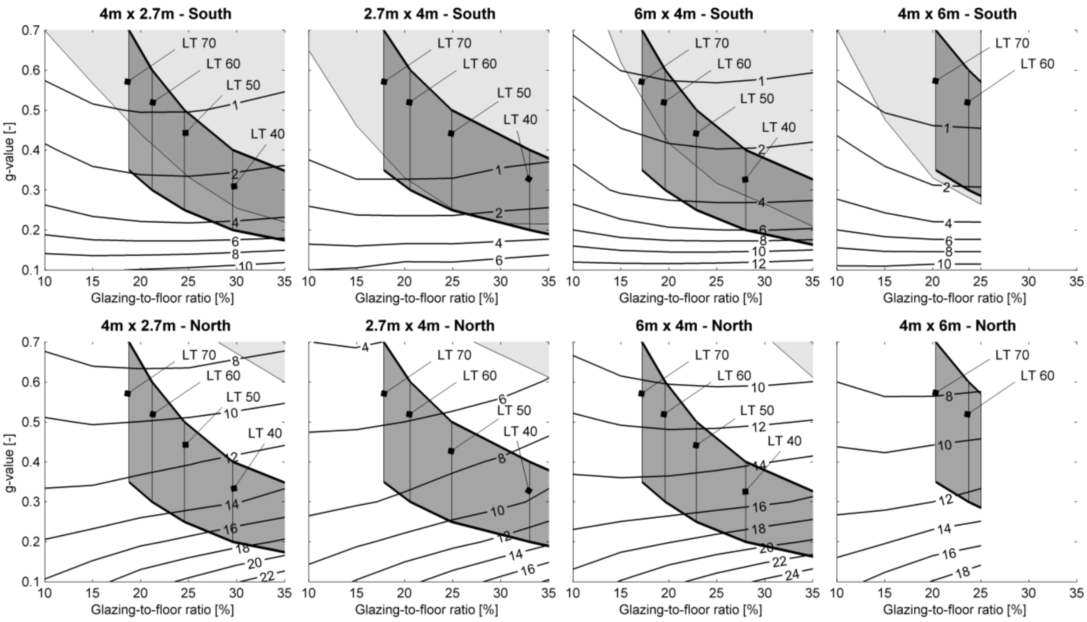

Figure 4: Contour plot of space heating demand for various g-values and glazing-to-floor ratios, indicating overheating and the specified daylight target for two different room sizes with a width-to-depth ratio of 1:1.5 and 1.5:1 and for a glazing U-value of 0.5 W/m2K.

As Figure 4 shows, for both south- and north-oriented rooms, wide room dimensions (width-to-depth ratio greater than 1) lead to higher space heating demand but less overheating than deep dimensions due to increased heat losses through the façade. Furthermore, the smaller the floor area of the geometry, the smaller the space heating demand. Small deep geometries are therefore preferable from the perspective of space heating demand. From a daylight point of view wide rooms with shallow depth should be preferred over small deep rooms. To achieve the same daylight access in deep rooms as in wide rooms with the same floor area, a larger glazing-to-floor ratio is generally needed. This will result in an increase in space heating demand, especially when high U-values are used, which could outweigh some of the benefits of deep rooms in terms of energy consumption. As the two deep room dimensions in Figure 4 show, there is a major problem that in deep or very narrow south-oriented rooms, either the daylight conditions or the thermal comfort must be compromised when a window design is chosen. For deeper rooms facing north, the space of solutions is restricted, not by overheating, but by the physical limitations of the geometry to provide the daylight target. This is also illustrated in Figure 5 for all the room geometries investigated and for light transmittances of 0.5–0.7. Figure 5 indicates the glazing-to-floor ratios that can be used in combination with clear glazing or glazing with ideal solar control (see Section 2.3) without resulting in overheating. The glazing-to-floor ratios needed to achieve the specified daylight target for each light transmittance are also illustrated. It is then interesting to see the glazing type and glazing-to-floor ratios that can be used to achieve the daylight target or even provide more daylight without resulting in overheating.

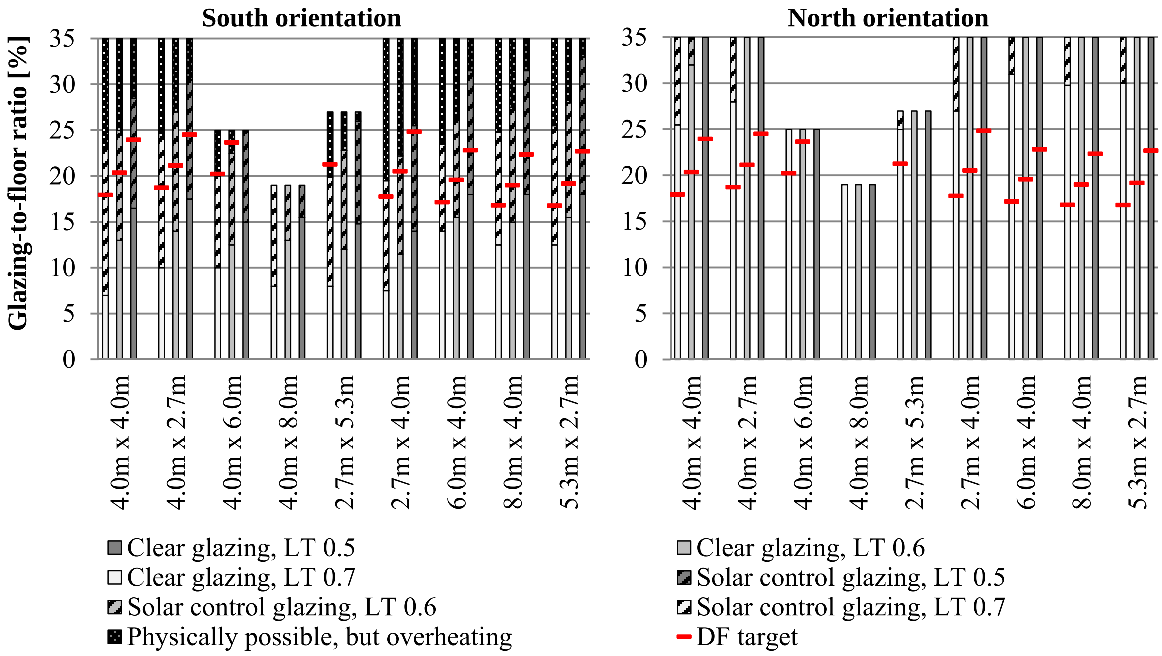

Figure 5: Indication of glazing-to-floor ratios and glazing types that can be used to achieve the daylight target (DF target) without overheating for light transmittances of 0.7, 0.6 and 0.5 for various room geometries.

As can be seen in Figure 5, all south-oriented rooms, except for rooms with dimensions of 4m x 6m, 4m x 8m and 2.7m x 5.3m, are able to achieve the daylight target without overheating. However, this requires the use of glazing products with some degree of solar control (daylight efficiency above 1). For north-oriented rooms, none of the geometries experience problems with overheating before achieving the daylight target, even when clear glazings are used. Figure 5 also shows that the room with dimensions of 4m x 8m is not able to achieve the daylight target due to physical limitations and that rooms with dimensions of 4m x 6m and 2.7m x 4m can only achieve the target for light transmittances of at least 0.6 and 0.7, respectively. In general, it can be concluded that for rooms with a depth greater than 5m, the daylight target cannot be achieved without overheating or cannot be achieved at all due to the physical limitations of the geometry. This corresponds well with common rules of thumb with regard to daylight penetration. When considering geometries that can achieve the daylight target without overheating, glazing-to-floor ratios of approximately 17–25% are needed to achieve the specified daylight target for light transmittances of 0.7–0.5. Within this range, of course, a slight variation in the glazing-to-floor ratio needed to achieve the daylight target is seen across the different geometries. This is close to the recommendations in the Danish building code, which states that a glazing-to-floor ratio of 15% is needed for a light transmittance of 0.75.

4 Discussion

The selection of beneficial window solutions in terms of space heating demand, thermal environment and daylight availability requires knowledge about the properties of the specific product as well as the different geometry factors that are related to its application, such as window size, room geometry and orientation. Due to the narrow space of solutions in south-facing rooms, for example, it is difficult to find a set of product parameters that applies for all building layouts and window distributions, because the maximum allowable g-value in terms of overheating is highly dependent on the glazing-to-floor ratio. Another example of how successful window solution selection depends on the interrelationship between products and design is the potential design conflict in side-lit deep or narrow south-oriented rooms. The choice of such room dimensions means that either thermal comfort or daylight must be compromised if additional cooling or alternative options that could expand the space of solutions, such as increased venting (for example using cross ventilation), special shading systems, etc., are not used. Moreover, the reduced need for high g-values in south-oriented rooms implies that permanent solar shading solutions, such as solar-coated glazing products with high daylight efficiency, can be a robust, user-friendly and cost-effective alternative to dynamic solar shadings. As can be seen from the space of solutions for south-oriented rooms, however, this depends on both glazing-to-floor ratio and U-value. If a glazing-to-floor ratio of 35% is desirable and a U-value of 0.9 W/m^{2}K is used, the maximum allowable g-value in terms of overheating will be lower than the g-value at which the reduction in space heating starts to stagnate. In this case, the use of a glazing with higher g-value in combination with dynamic solar shadings would lead to relatively high benefits in terms of space heating demand compared to a permanent solution. On the other hand, if smaller glazing-to-floor ratios with high light transmittance are used, the allowable g-value in terms of overheating is higher than the g-value at which the potential reductions in space heating demand start to stagnate. In this case, the positive effect of using a higher g-value in combination with dynamic solar shadings would be relatively small. Furthermore, the lower the glazing U-value, the more flexible the glazing-to-floor ratio can be when using permanent solutions.

The parametric analyses and the charts illustrating the space of solutions in this study are an invitation to an open discussion of the link between various design and performance parameters as well as the possibilities and potential conflicts related to window design in ‘nearly zero-energy’ houses. In principle, all the performance parameters and the chosen targets can be tested for sensitivity to e.g. different insulation thicknesses, different user patterns and adaptive models for thermal comfort, different ventilation systems, and different daylight targets. The study has shown that when reasonable geometries are used the daylight target investigated can be achieved in Danish houses without the need for mechanical cooling. Considering that the results in this study come from performing investigations at room level, overheating found in south-oriented rooms is seen as a worst case scenario, because, in reality, different rooms in a residential building are partly or fully connected, allowing for heat transfer and interzonal air flow. In warmer climates, where mechanical cooling is needed to avoid overheating, the value of daylight compared to the energy used for cooling may give rise to several discussions, such as for example whether it is reasonable to dimension the window sizes in south-oriented rooms on the basis of targets for daylight availability under overcast situations. In our study, more flexibility with regard to the choice of window size and geometries was found for north-oriented rooms than for south-oriented rooms. In relation to this, however, one must remember that this is when the two orientations are dimensioned for equal daylight conditions under a standardized overcast sky, i.e. without taking orientation and direct sun into account. For the two orientations to have comparable daylight availability over time under realistic sun and sky conditions, either the glazing-to-floor ratio towards the south must be decreased or the glazing-to-floor ratio towards the north must be increased. So, a climate-based approach for the evaluation of daylight may be needed. However, further studies on visual comfort in south-oriented rooms and the effects of daylighting on human health, comfort and well-being, amongst others will be needed to determine how comparable targets for north- and south-oriented rooms can be set in residential buildings.

With the greater flexibility in north-oriented rooms, where the risk of overheating is close to insignificant, it could also be argued that slightly larger glazing-to-floor ratios should generally be used here than in south-oriented rooms. For high U-values this may have some consequences on space heating demand, but when weighed at the level of the whole building, this might still be acceptable when taking the low space heating demand in south-oriented rooms into account. Moreover, if U-values below 0.5 W/m^2K are used in north-oriented rooms, it might even be possible to talk about a 'neutral' glazing solution that is applicable for any glazing-to-floor ratio both from the perspective of space heating demand and thermal indoor environment. Realistic ranges for the high g-values that are preferred for reducing space heating demand in north-oriented rooms, however, must be seen in relation to technical considerations that are connected with U-value. Where the use of a U-value of 0.3 W/m^2K corresponds to the use of a four-layer glazing, low-iron glazing will be needed to obtain higher g-values. However, using a glazing with U-value of 0.3 W/m^2K and g-value of for example 0.4 would still result in a significantly lower space heating demand than using a glazing with U-value of 0.5 W/m^2K and g-value of 0.5.

5 Conclusions

The effect of window size and glazing parameters on space heating demand, daylight availability and thermal indoor environment has been investigated for various room geometries in Danish 'nearly zero-energy' houses. On basis of the results, the main findings are as follows:

- In south-oriented rooms, there is an upper limit for the amount of solar gain that can be utilised efficiently. The optimum glazing-to-floor ratio in terms of space heating demand was found at approximately 15–20% and reductions in space heating demand from increasing the g-value tend to stagnate at g-values in the interval 0.3–0.5, depending on U-value. In order to achieve the daylight target without overheating, windows must be carefully dimensioned on the basis of the daylight target and solar-coated products with close to ideal daylight efficiency must be used. When glazing products with a light transmittance of 0.5–0.7 are used, overheating occurs at g-values around 0.3–0.4. High light transmittances and low U-values generally provide the best match between the maximum allowable g-values from the perspective of overheating and the point at which the reductions in space heating demand with increased access to solar gains tend to stagnate.

- In north-oriented rooms, glazing-to-floor ratio and g-value can be chosen with little risk of overheating, and the use of high g-values to reduce space heating demand is important for all the variables investigated.
- Large glazing-to-floor ratios generally lead to increased space heating demand for both orientations when the glazing U-value is above 0.5 W/m^{2}K. With the use of U-values lower than 0.5 W/m^{2}K, the use of large glazing-to-floor ratios is beneficial for the reduction of space heating demand in north-oriented rooms, while in south-oriented rooms, this has close to insignificant effect on space heating demand. Due to the flexible space of solutions in north-oriented rooms, the potential negative effects on space heating demand in choosing large glazing-to-floor ratios are generally smaller in north-oriented rooms than in south-oriented rooms.
- Whereas small and deep rooms are preferable from the perspective of space heating demand, wide shallow rooms are preferable from the daylight point of view. In south-oriented rooms with depths greater than approximately 5m or for very narrow room widths, there is a high risk that the daylight target cannot be achieved without overheating or cannot be achieved at all. Greater flexibility with regard to geometry was found in north-oriented rooms, but one should keep in mind this is when the daylight availability for both orientations is evaluated under a standardized overcast sky, without taking orientation or direct sun into account.

These conclusions illustrate the importance of considering both the properties of a specific glazing product and the various geometry factors that are related to its application in the search for window solutions that are beneficial in terms of all three performance parameters. Furthermore, the study has exemplified an approach by which window solutions with minimum space heating demand can be chosen in a space of solutions for each geometry defined by targets for minimum daylight availability and overheating through the application of diagrams. This method has provided important knowledge about the link between various design and performance parameters and is an invitation to an open discussion of possibilities and potential conflicts related to cost-efficient window design in nearly-zero energy buildings.

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Paper III

WinDesign: a simple calculation tool for selection of windows in residential buildings.

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WINDESIGN: A SIMPLE CALCULATION TOOL FOR SELECTION OF WINDOWS IN RESIDENTIAL BUILDINGS

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Abstract

Windows affect energy consumption for heating and cooling of buildings and the thermal indoor environment. While the use of window energy rating systems allows for an easy assessment and comparison of the energy performance of the many existing types of windows, the choice of the best window for an actual building is a complicated design decision that might require the use of building simulation. Standard building simulation tools do not enable an easy comparison of different window designs, even though this is very important in the early stages of the building design process. This paper presents a user-friendly calculation tool based on simple input data and methods for the purpose of assisting engineers and architects during the process of selecting suitable windows for residential building design. The tool is organised in four steps, which together represent an analysis of how windows in a specific building design perform with regard to energy consumption, thermal indoor environment, and cost. The analyses in the steps gradually increase in level of detail and support the design decisions throughout the design process. Validation of the simplified methods used in the tool showed overall good comparison with results from dynamic simulations in EnergyPlus. Moreover, because the tool only needs limited input data, the user could benefit from using the tool in the early phases of the design process, where the most important decisions are made.

Keywords: Fenestration, Window design, Simulation, Energy performance, Thermal indoor environment.

1 Introduction

Windows are known as having a large impact on the energy performance and thermal indoor environment in buildings and it is therefore important to select the right window design from the early stages of the design process. As the selection of the right window design is usually not immediately obvious, several window energy rating systems (WERS) have been developed in different countries [1-5] to assess the energy performance of the many existing types of windows, and to encourage development of new window products. There are several ways of establishing a WERS, but most of them consider different window properties such as thermal transmittance (U-value) and total solar energy transmittance (g-value) and are based on estimation of solar gains and heat losses due to windows by calculation of the energy balance of windows installed in small residential buildings [3, 4]. However, a WERS can also be adapted for office buildings and include, for example, energy savings from the utilization of daylight [6]. While WERS might seem a practical tool for evaluating the energy performance of windows and allow easy and quick comparison of various windows, the energy performance of a window depends not only on the window properties, but also on climate, interaction with the building and its orientation, internal loads etc.

In a study by Karlsson and Roos [7], three different WERS were compared to evaluate how complex a WERS needs to be in order to provide reliable a reliable energy rating system that can be applied to different buildings in different climates and orientations. A simple linear ‘Danish’ model that includes the degree-days or degree-hours and the weighted total solar radiation throughout the heating season [3] was compared to the ‘Karlsson’-model which uses hourly climate data and is able to take building type and useful solar gains into account based on the balance temperature [5] and to a detailed hourly dynamic model taking into account data such as UA-values, ventilation and internal loads. Results from the study showed that the more advanced models which take into account building type and use hourly climate data show best fit with results obtained from detailed building simulations. However, a simple linear model was shown sufficient within certain regulations if its coefficients were evaluated and fitted for different climate zones and buildings. Similarly, investigations in different methods to obtain energy gains and losses due to windows to establish a WERS by Urbikain and Sala [8] showed that a distinction between building type and useful solar heat gains is needed at least. However, since the choice of the best window for an actual building is a complicated design decision, the use of detailed simulations gave most precise results.

Many tools exist for thermal simulation of buildings, but few are focused on window design (especially in residential buildings). Furthermore, detailed simulation tools such as EnergyPlus [9], Esp-r [10] and TRNSYS [11] often require detailed input describing building geometry and construction, systems layout, and control strategies, and they require a significant level of expert knowledge. Therefore, they usually not suitable for use in the early stages of the design process where important decisions are made. Moreover, detailed simulation tools do not enable an easy comparison of the effect of window design varying in orientation, configuration and size on energy consumption and thermal indoor environment. Few examples of tools created for supporting decisions with regards to window design in the early design stages in residential buildings are RESFEN [12, 13], GenWin [14] and WinSim [15].

Generally, in contrast to the many investigations of the physical parameters of windows, when it comes to simplified window selection tools for use in the early design stages, there has not been much detailed research and there is still a need for tools that can be standardized and used for international purposes.

This has resulted in the development of a simplified tool to help with the selection of window design in residential buildings. The tool combines an evaluation of the energy balance of windows based on calculation of their Net Energy Gain (NEG) and simulation of windows in an actual building, both with regard to energy consumption and indoor climate, in accordance with the calculation methods in the European Standard EN ISO 13790 [16]. The tool, named WinDesign [17], can be used by architects and engineers during the design phase of new buildings as well as for the renovation of existing buildings, and it allows a comparison of various windows and user-defined scenarios in just one simulation. One of the aims of the tool is to be user-friendly, so it is based on few input data and has been built in Microsoft Office Excel 2007 using built-in functions and User Defined Functions (UDF) programmed in Visual Basic for Applications (VBA). In addition, the open Microsoft Excel and Visual Basic based programming makes it easy to adjust and process data and provides a familiar environment and platform for the user.

This article describes the concept and calculation procedures behind the WinDesign tool. Furthermore, results from validation of heating and cooling demands and indoor air temperatures by comparison with a detailed simulation tool are presented.

Nomenclature

E_{Net}	Net energy gain (kWh/m^2)
I	Solar radiation (kWh/m^2) during heating season, corrected for the dependency of the total solar energy transmittance on the incidence angle
g_w	Total solar energy transmission of the window (-)
D	Number of degree hours during heating season (kKh)
U_w	Thermal transmittance of window at incidence angle of 0° (W/m^{2}K)
$I_{sun,corr}$	Solar radiation corrected for shading from exterior objects, (W/m^2)
F_{hor}	Shading reduction factor from the horizon (-)
F_{ov}	Shading reduction factor from overhangs (-)
F_{fin}	Shading reduction factor from side fins (-)
I_{sun}	Original solar radiation (W/m^2)
$F_{sh,ob}$	Shading reduction factor due to objects exterior to the window (-)
$F_{sh,with}$	Utilisation factor for movable solar shading (-)
$E_{windows}$	Energy consumption of windows (kWh/m2)
A_w	Window area (m^2)
G	Number of degree hours calculated for a reference indoor temperature of 20ºC (kKh)
η_{gn}	Dimensionless utilisation factor for solar gains (-)
η_{ls}	Dimensionless utilisation factor for heat losses (-)
A_{sol}	Effective collecting window area for a given orientation and tilt angle (m^2)
I_{sol}	Total incident solar radiation per square metre of window area for a given orientation and tilt angle (kWh/m^2)
A_{floor}	Heated floor area of the dwelling (m^2)
$I_{setpoint}$	Illuminance at set point (lx)
$DF_{setpoint}$	Daylight factor at set point (%)
$I_{ext,hor}$	Illuminance on exterior horizontal plane without corrections for shade from exterior objects taken into account (lx)
P	Amount of power supplied by artificial lighting system (W)
$I_{thresholdvalue}$	Threshold value for activation of artificial lighting system (lx)
$I - I_{ref}$	Investment cost (monetary unit)
$E_{ref} - E$	Annual savings (kWh)
d	Net discount rate (-)
n	Economic evaluation period (years)

Index

CS	Cooling season
HS	Heating season
i	Specific window i
max	Maximum
min	Minimum

2 Workflow and calculation procedures

WinDesign is organized in four different steps, each corresponding to a specific analysis. The idea is that the different steps gradually increase in level of detail and support the design decisions throughout the design process. In each step, a number of different scenarios can be defined where it is possible to vary certain parameters. Based on the results from the four steps, the various scenarios can be compared and the most appropriate window design with regard to energy consumption, thermal indoor environment, cost and to some extent also daylight (based on electricity consumption for artificial lighting) can be selected, see Figure 1.

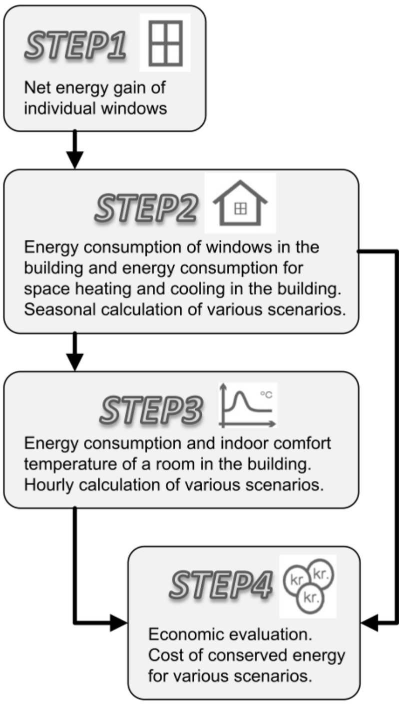

Figure 1: Flowchart of the calculations performed in the different steps in WinDesign.

Each step has its own calculation module and user interface developed to facilitate the workflow suggested in Figure 1. In the following, the four steps are briefly described, including the calculation procedures and some of the new features that have been implemented in the tool:

- a method has been implemented to calculate the solar irradiation on windows with arbitrary tilt angle and orientation,
- it has been made easier to use weather data from countries other than Denmark,
- an estimation of the energy consumption for artificial lighting has been added,
- the hourly calculations have been expanded from a single-zone calculation to a multi-zone calculation, though without thermal coupling between zones
- in both Step 2 and Step 3, it has been made possible to investigate the effect on the energy consumption for heating and cooling of the building from building components other than windows, e.g. walls, floors, etc. and
- as an advance in the use of the tool, an import capacity from ArchiCAD has been implemented [18].

2.1 Step1: Net energy gain of individual windows

In Step 1, the general energy performance of a wide range of individual windows is evaluated based on the concept of Net Energy Gain (NEG). In order to do so, the user can create various windows based on knowledge of configuration, size and components (glazing, frame/sash, mullions/transoms and glazing bars). Window components can be selected from a database, but it is also possible to define new components in the database. The net energy gain E_{Net} (kWh/m^2) is calculated for each window using Equation 1 defined by Nielsen et al. [3] for single-family houses. After calculation of the net energy gain, the best-performing windows can be selected and used in the further analysis. When design of Danish residential buildings is considered, the user should keep in mind the requirements for minimum NEG as defined in the Danish Building Code [19].

$$E_{Net} = I \cdot g_w - D \cdot U_w \quad (1)$$

The solar radiation I (kWh/m^2), and the degree - hour D (kKh) are automatically calculated based on the available weather data. The weather data required for calculations in WinDesign consists of hourly values for external temperature (°C), direct normal solar radiation (W/m^2), horizontal diffuse solar irradiation (W/m^2), and global horizontal solar illuminance (lx). These values can be extracted in WinDesign from standard weather data found in the IWEC-data format (International Weather data for Energy and Climate simulations, [20]). However, for Denmark, calculations are performed by using weather data for the Design Reference Year (DRY) [21].

2.2 Step2: Energy performance of windows in the building

The aim of Step 2 is to calculate the energy consumption of the windows in a specific building for the heating and cooling season and to document the building´s energy consumption for space heating and cooling. The calculations are performed in accordance with the seasonal method described in the European standard EN ISO 13790 [16]. The specific heating and cooling season needed for the calculations are automatically calculated based on seasonal average weather data.

Calculations of the energy consumption of the windows and energy consumption for space heating and cooling are based on considering the entire building as a single thermal zone, although the user has the option of providing input data for windows in several rooms. To construct the thermal model of the entire building in this step, only simple input data, such as the heated floor area, floor-to-ceiling height, thermal transmittance of the building envelope components (UA value), internal heat gains, infiltration rate, ventilation rate, use of heat exchanger, and heating and cooling set points are required. If the heat exchanger is activated during the heating season, it can be bypassed during the cooling season. As suggested in the seasonal method in EN ISO 13790 [16], the internal heat capacities of the different building components are taken into account by one effective heat capacity for the entire building. As a starting point, input with regard to the internal heat gains, infiltration rate and ventilation rate are constant values for both the heating and cooling season. However, experienced users have the option to change this.

Windows for the specific dwelling can be selected based on Step 1, or the user can define new windows by providing area A_w (m^2), thermal transmittance U_w (W/m^2K), and total solar energy transmittance g_w (-). To calculate energy consumption of the windows in a specific home, the orientation, tilt angle, external obstructions from the horizon, overhangs and/or fins, solar shading coefficient, and control strategy for solar shading also need to be defined for each window. Up to five different user-defined scenarios of windows, U-values, internal gains, etc. can be implemented and calculated in this step, which also allows for a quick parameter analysis and an optimisation of building components other than windows.

2.2.1 Calculation of solar radiation on windows with arbitrary tilt angle

It is possible to define windows with an arbitrary tilt angle and orientation in WinDesign. The total solar radiation on each window is calculated in accordance with well-documented methods for estimating direct, diffuse and ground reflected solar radiation [22, 23]. However, calculations of the incidence angle have been simplified by just calculating one incidence angle for the midpoint of the hour instead of using an average incident angle for the hour in question. Furthermore, in Step 2, the total solar radiation on each window is summed into a monthly average value.

2.2.2 Shade from exterior objects

As previously mentioned, external obstructions from the horizon (e.g. neighbouring houses and trees), and overhangs and/or fins need to be defined for each window in WinDesign, because shade from these exterior objects can influence the direct component of the solar radiation. Moreover, when these objects are close to the building, their shade can also affect the diffuse and reflected component of the solar radiation. It is, however, assumed in WinDesign that shading from overhangs and fins only affects the direct and diffuse radiation and not the reflected part of the radiation. Shading factors for all exterior objects are calculated in accordance with EN ISO 13790 [16]. If the original solar radiation is multiplied by these shading factors, the solar radiation corrected for shading from exterior objects, $I_{sun,corr}$ (W/m^2) can be found using Equation 2.

$$I_{sun,corr} = F_{hor} \cdot F_{ov} \cdot F_{fin} \cdot I_{sun} = F_{sh,ob} \cdot I_{sun} \quad (2)$$

2.2.3 Solar shading

Solar shading devices can be used in both Steps 2 and 3. In Step 2, the user can select between solar shading that is fixed or movable. Both types of solar shading devices are defined by their shading coefficient, which is the ratio between the total solar energy transmittance of the window with the solar shading device activated and the total solar energy transmittance of the window alone. This shading factor is then added to the g-value of the window. If the shading device is fixed, the solar shading is activated the entire year. However, if the shading device is movable, a utilisation factor is used to simulate the in-use time of the shading device for situations where the solar radiation exceeds 300 W/m^2, see Equation 3. However, this can be changed by experienced users.

$$F_{sh,with} = \left(\sum\nolimits_{if\ I>300W/m^2} I\right) \Big/ \sum I \quad (3)$$

2.2.4 Energy consumption of windows in a specific building

After the calculation of the total solar radiation on each window, the energy consumption of the windows during the heating and cooling seasons ($E_{windows,HS}$, $E_{windows,CS}$, kWh/m^2) can be calculated using Equations 4 and 5 [16].

$$E_{windows,HS} = \sum_i (U_{w,i} \cdot A_{w,i} \cdot G_{HS} - \eta_{gn,HS} \cdot F_{sh,ob,i,HS} \cdot A_{sol,i,HS} \cdot I_{sol,i,HS}) / A_{floor} \quad (4)$$

$$E_{windows,CS} = \sum_i (F_{sh,ob,i,CS} \cdot A_{sol,i,CS} \cdot I_{sol,i,CS} - \eta_{ls,CS} \cdot U_{w,i} \cdot A_{w,i} \cdot G_{CS}) / A_{floor} \quad (5)$$

2.3 Step 3: Hourly calculation of energy consumption and thermal comfort in a room

In Step 3, the thermal indoor environment is evaluated on an hourly basis for one or more rooms (or the entire home modelled as a single zone) for the scenarios defined in Step 2. The results are represented in terms of the number of hours with a temperature above a user-defined maximum comfort temperature for each room, and the temperature development can also be graphically represented. In addition to the evaluation of the thermal indoor environment, the energy consumption for space heating and cooling needed to achieve the desired indoor temperature is calculated on an hourly basis. As a basis for the hourly calculation, the “simple hourly method” described in EN ISO 13790 [16] has been used. In previous versions of the tool, the calculations were simplified to a single-zone simulation model, only allowing the calculation of the thermal indoor environment and energy consumption for one room at a time. In the latest version, the thermal model is based on the independent multi-zone calculation defined in EN ISO 13790 [16]. This means that no thermal interaction between the rooms is taken into account.

To define the various rooms in this step, additional information is needed about the total thermal transmittance of the building envelope and the internal floor area of each room. The user must also specify whether venting is used to cool the building and when the venting is activated. Furthermore, the systems defined in Step 2 (solar shading, ventilation, use of heat recovery, bypass of heat recovery, heating and cooling) can also be activated (or deactivated) to control the thermal indoor environment and calculate the energy consumption for space heating and cooling. In addition to these calculations, a method of estimating the electricity needed for artificial lighting in each room has been added, and a control strategy to maintain a comfortable thermal indoor environment using minimal energy for heating and cooling systems has been implemented.

2.3.1 Electricity use for artificial lighting

To estimate the electricity needed for artificial lighting, the amount of electrical power needed to maintain a certain level of light in each room is calculated based on the daylight factor (DF) inside each room. WinDesign does not include a daylighting module, so the daylight factor has to be calculated using additional software. Based on the daylight factor, the light level at a set point in each room can be calculated for each hour using the following equation:

$$I_{setpoint} = DF_{setpoint} \cdot I_{ext,hor} \quad (6)$$

The light level at the set point is then used to control the electrical light in a simple way: if lighting at the set point is insufficient, i.e. below the minimum requirement of threshold settings given by the user, the artificial lighting system is turned on. Once turned on, the lighting system is assumed to be intelligent and is therefore able to modulate the light level to meet the requirements without exceeding the threshold value. The modulating system is assumed to be linear. Moreover, a time control is included to ensure that the lighting system is turned off outside occupancy hours. The amount of artificial light needed to supply sufficient light at the set point is then calculated as follows:

$$P = \begin{cases} \dfrac{P_{max} \cdot I_{setpoint}}{I_{thresholdvalue}} & if\ I_{setpoint} \leq I_{thresholdvalue} \\ \\ P_{min} & if\ I_{setpoint} > I_{thresholdvalue} \end{cases} \qquad (7)$$

However, since the calculation of the electricity used for artificial lighting is based on external calculations of daylight factors in each room, the result only gives an estimation of the real electricity use for artificial lighting.

2.3.2 Control strategy

The overall aim of the control strategy implemented in the tool is to maintain the indoor temperature in each of the rooms within certain comfort limits without using any energy, or as little energy as possible, for the heating and cooling systems. To this end, first the tool uses the heat capacity of the dwelling as storage for the solar radiation that enters through the windows to achieve the user-defined heating and cooling set points at the end of each hourly time step. If the indoor air temperature calculated at the end of each time step after using the heat capacity of the dwelling is higher than the cooling set point, venting will be activated. If it is lower than the heating set point temperature + 1°C, the heat exchanger is activated. Then, if the indoor air temperature, corrected for venting or the use of the heat exchanger at the end of the time step still exceeds the heating or cooling set point, mechanical heating or cooling is activated. If no mechanical cooling is available, the resulting indoor air temperature at the end of each time step is calculated and the number of hours with overheating above the user defined maximum comfort temperature is reported.

2.4 Step 4: Economic evaluation

In Step 4, a simple economic evaluation, based on the criterion of the cost of conserved energy (CCE), can be made to compare costs and savings for the various design scenarios defined in Step 2 and Step 3. With one of the scenarios defined in Step 2 or Step 3 selected as reference scenario. The CCE (monetary unit/kWh) for the other scenarios is calculated as follows [24]:

$$CCE = \frac{I - I_{ref}}{E_{ref} - E} \cdot \frac{d}{1 - (1 + d)^{-n}} \qquad (8)$$

The user can compare the results from the calculations for the various scenarios with the price of the energy source used to provide heating and cooling to the home. The CCE will then indicate whether it is cheaper to save energy or to consume it. It should be mentioned, though, that this formula used for the calculation of the CCE is rather simple and only takes into account the initial investment cost. If, for example, maintenance costs need to be taken into account or more accurate results are required, more detailed calculations need to be carried out.

3 Validation

Calculations in Step 2 and Step 3 in WinDesign are performed in accordance with methods 1 and 2 in the European standard EN ISO 13790 [16], respectively. Several reasons underlie the choice of the methods specified in this standard for the development of the tool. First, the methods in the standard comply with the EPBD requirements for the definition and adoption of a common methodology for calculating energy consumption [25]. Second, the methods rely on relatively few input data, which makes them suitable for use in the early design phases, and results in rapid simulations. Today, the standard has been taken into use in several countries and the quasi-steady-state method has been adopted as an official method for documenting energy consumption [26, 28]. Several papers also report on simulation models based on this model and its predecessor [28, 29]. The simple hourly calculation method is less used, but an application can be found in the Turkish Technical Standard [30].

The widespread adoption of the quasi-steady-state method means that the accuracy of the method has been investigated and compared with results from dynamic simulation tools in several studies [31-34]. Results from these studies showed that the method is adequate in most cases for determining monthly heating and annual heating energy consumption in residential buildings, but could benefit from dynamic parameters related to national context for calculation of the gain utilization factors. The method also has some weaknesses with regard to the prediction of cooling demand due to the mismatch between gains and losses that affects the utilization factors [35]. For a better prediction of cooling demand, the simple hourly method is recommended.

3.1 Case study

In this study, validation of the simple hourly method in WinDesign for prediction of heating and cooling demand and thermal indoor environment in residential buildings is carried out through comparison with results from the dynamic building simulation tool, EnergyPlus [9], which has been widely validated for its accuracy and consistency. The building chosen for analysis is a representation of the size and layout of a typical Danish single-family house. The house consists of one storey and has a heated floor area of 163 m^2. Of interest is to see how the results compare for different zones in the single-family house, as the simple hourly method implemented in WinDesign does not consider any interaction between thermal zones. Therefore, a 6-zone model of the single-family house, see Figure 2, was used for comparison with a 6-zone coupled thermal model in EnergyPlus taking into account heat transfer by thermal transmission between the different zones. For illustration, also a 6-zone adiabatic model was considered in EnergyPlus.

To determine the energy demand under ideal conditions, the ‘ideal loads air system’, which has an infinite heating and cooling capacity, was used in EnergyPlus [36]. Moreover, other inputs, such as weather data and heat transfer through the ground were harmonized for consistency in the compared models [35, 37].

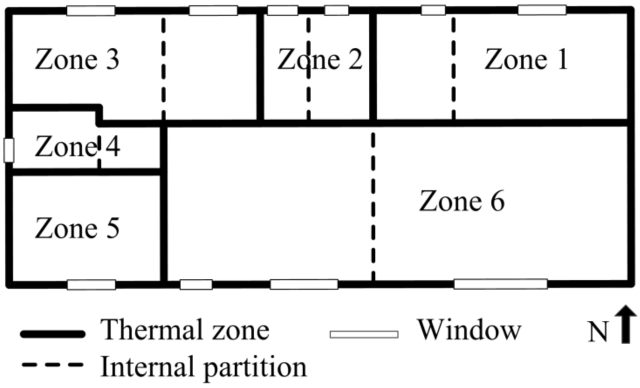

Figure 2: Floor plan of the house and illustration of thermal zones.

The results were compared for a range of parameters, such as insulation level, window size, window type, orientation and thermal mass, as indicated in Table 1. A constant ventilation rate of 0.5 air changes per hour with a heat recovery rate of 85% is used and infiltration is set to 0.05 h^{-1} through the whole year. Neither venting nor the use of solar shading devices has been considered. Design values for internal gains were set to 3.5 W/m^2 for lighting and equipment and 1.5 W/m^2 for internal gains from people in accordance with standard practice in Denmark [38]. The heating set point was fixed at 20^{o}C in all simulations and the cooling set point was fixed at 26^{o}C for cases with an active cooling system. Cases without active cooling allowed for a comparison of degree-hours with temperatures above 26^{o}C.

Table 1: Variables used for analyses.

Parameter	Variable	
Orientation	N/S[3)]	
Glazing-to-floor ratio[1)] (%)	10/20/30/40/50	
Effective heat capacity[2)] (J/m^2K)	$3.5 \times 10^5/3.0 \times 10^5/2.5 \times 10^5$	
	Insulation level 1	*Insulation level 2*
U_{wall} (W/m^2K)	0.19	0.1
U_{roof} (W/m^2K)	0.16	0.08
U_{floor} (W/m^2K)	0.17	0.09
	Window type 1	*Window type 2*
U_{window} (W/m^2K)	1.1/0.7	0.7
g_{window} (-)	0.61/0.41	0.41

1) Based on internal floor area.

2) Indicated only for glazing-to-floor ratio of 10%. The indicated effective heat capacity is further adjusted to take into account an increase in glazing-to-floor ratio.

3) The orientation indicates rotating the house as a whole with the original south façade turned towards the desired orientation.

3.2 Results

Figure 3 illustrates annual cooling and heating demand by use of the simple hourly method when averaged at the level of the whole building and compares it with results from dynamic simulations using a coupled thermal zone model in EnergyPlus.

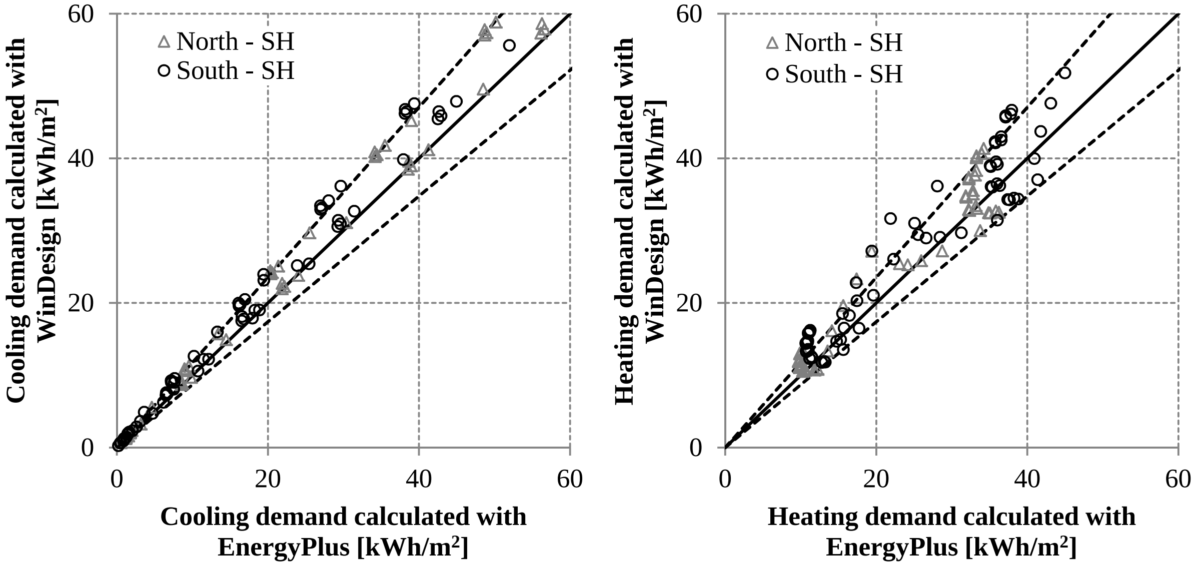

Figure 3: Comparison of cooling and heating demand obtained from the use of the simple hourly method (SH) in WinDesign with cooling and heating demand from dynamic simulations using a 6-zone coupled thermal model in EnergyPlus. The dotted lines represent a deviation of 15%.

As can be seen in Figure 3, results for cooling demand obtained by using the simple hourly method show generally good correspondence with results from dynamic simulation for both north and south orientation as most of the points comparing cooling demand can be found between the two dotted lines which represent a deviation of 15%. Two trends can, however, be identified: points showing very small deviation, and points illustrating an overestimation of cooling demand around 15%. This reflects the different insulation levels investigated. The largest deviation corresponds to cases with a very high insulation level, whereas smaller deviations can be assigned to the use of a standard insulation level. Further investigations revealed that the same trends can also be found when compared to results from the 6-zone adiabatic model in EnergyPlus, but can result in slight underestimation of cooling demand for north orientation of a standard insulated house. Considering heating demand, see Figure 3, a clear trend can also be seen in the results for both north and south orientation. The trend represents the different glazing-to-floor ratios for each individual combination of parameters other than glazing-to-floor ratio as indicated in Table 1. Points resulting in an underestimation of heating demand represent small glazing-to-floor ratios, while large-glazing-to-floor ratios result in an overestimation of heating demand. In a standard insulated house, deviations are less pronounced and more or less within 15% deviation. However, in well-insulated houses overestimations at large-glazing-to-floor ratios exceed the 15% deviation.

When comparing to the adiabatic model, see Figure 4, a better fit between the results can be obtained for larger glazing-to-floor ratios. However, the differences in results seem to point to different dynamics used in both tools. This could be due to the thermal mass, which is taken into account in a more simplified way in the hourly method than in dynamic calculation tools and plays an important role in well-insulated buildings.

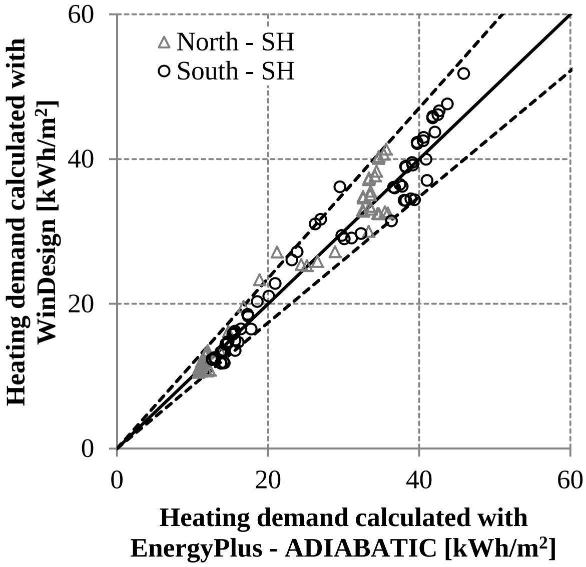

Figure 4: Comparison of heating demand obtained from the use of the simple hourly method (SH) in WinDesign with heating demand from dynamic simulations using a 6-zone coupled thermal model in EnergyPlus. The dotted lines represent a deviation of 15%.

For comparison, results for annual cooling and heating demand obtained from using the seasonal quasi-steady-state method in WinDesign are also illustrated and compared with results from dynamic simulations based on the use of the coupled thermal zone model in EnergyPlus, see Figure 5. These show similar trends as obtained with the simple hourly method when looking at heating demand, but result in larger discrepancies with regards to cooling demand, especially for south orientation. For a standard insulated house this corresponds well with findings by Corrado et al. [35], who found that the monthly and simple hourly methods generally show good correspondence with results from dynamic simulations during the heating season when the mismatch between gains and losses is low. This is also valid when comparing to the adiabatic model in case of a well-insulated house. During the cooling season, however, the monthly method overestimates the cooling demand. This is due to the loss utilization factor for cooling which is less realistic as the mismatch between gains and losses increases.

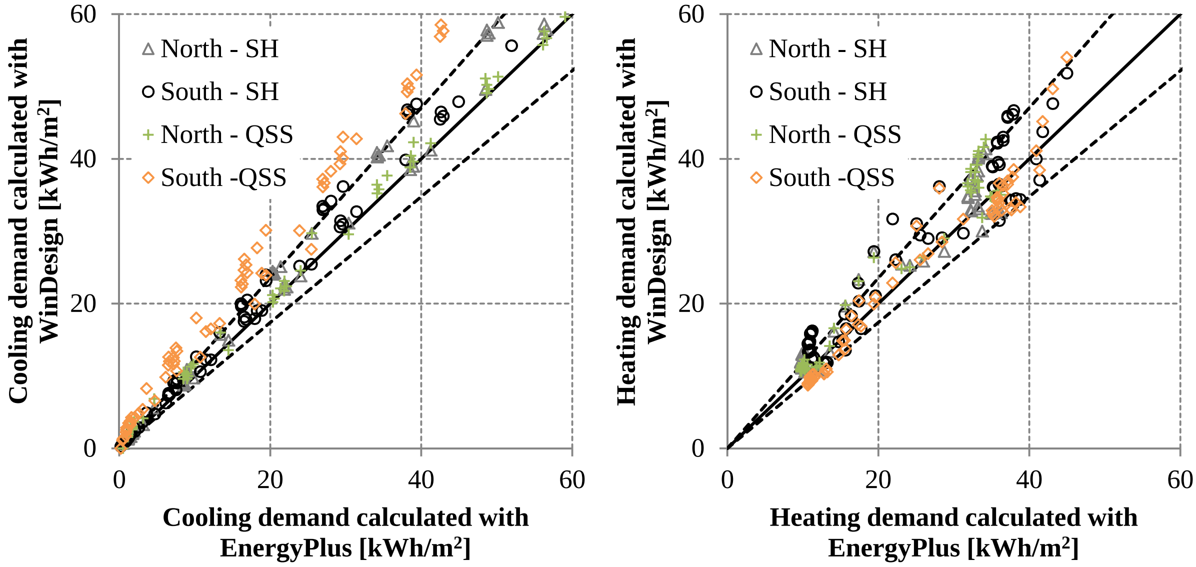

Figure 5: Comparison of cooling and heating demand from WinDesign obtained by using the quasi-steady-state method (QSS) and the simple hourly method (SH) with cooling and heating demand from dynamic simulations using a 6-zone coupled thermal model in EnergyPlus.

In the following, results from further investigations comparing cooling and heating demand and thermal indoor environment in the different thermal zones is presented. Table 2 illustrates average and standard deviation in difference between results from using the simple hourly method in WinDesign and dynamic simulations based on the use of the coupled thermal zone model in EnergyPlus.

Table 2: Average and standard deviation in difference between results for each thermal zone from using the simple hourly method in WinDesign and dynamic simulations based on the use of a coupled thermal zone model in EnergyPlus.

	Cooling - North		Cooling - South		Heating - North		Heating - South		Degree-hours with Tint>26°C - North		Degree-hours with Tint>26°C - South	
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
Zone 1	0.16	0.10	0.27	0.13	0.09	0.16	0.02	0.15	0.34	0.09	-0.01	0.21
Zone 2	-0.14	0.13	0.03	0.12	0.28	0.11	0.12	0.12	0.08	0.19	-0.49	0.39
Zone 3	0.06	0.07	0.22	0.10	0.24	0.13	0.07	0.10	0.21	0.08	-0.14	0.14
Zone 4	-0.09	0.10	-0.19	0.14	0.07	0.16	0.06	0.19	-0.03	0.14	-0.15	0.14
Zone 5	0.36	0.13	0.10	0.15	-0.20	0.15	0.02	0.21	0.28	0.21	0.32	0.09
Zone 6	0.06	0.08	0.07	0.18	0.08	0.12	0.33	0.12	0.12	0.16	0.27	0.09

The results show that for each of the individual thermal zones the simple hourly method gives reasonable results for the heating and cooling demands compared to a detailed model, even when results are averaged for the different combinations of parameters investigated, such as window size and insulation level. When looking at the degree-hours with temperatures above 26°C, the average differences and their standard deviation are slightly larger, but acceptable. Further investigation showed, however, better comparison with results from the adiabatic model, especially for a well-insulated house.

This is also demonstrated in Figure 6 and Figure 7 where the monthly temperature profiles for a standard insulated house and a well-insulated house, respectively, are compared for different glazing-to-floor ratios for south-orientation of Zone 1. This zone has been picked as it shows the largest average difference in indoor temperatures with degree-hours above 26°C when it is oriented towards the south (north-orientation of the house in Table 2).

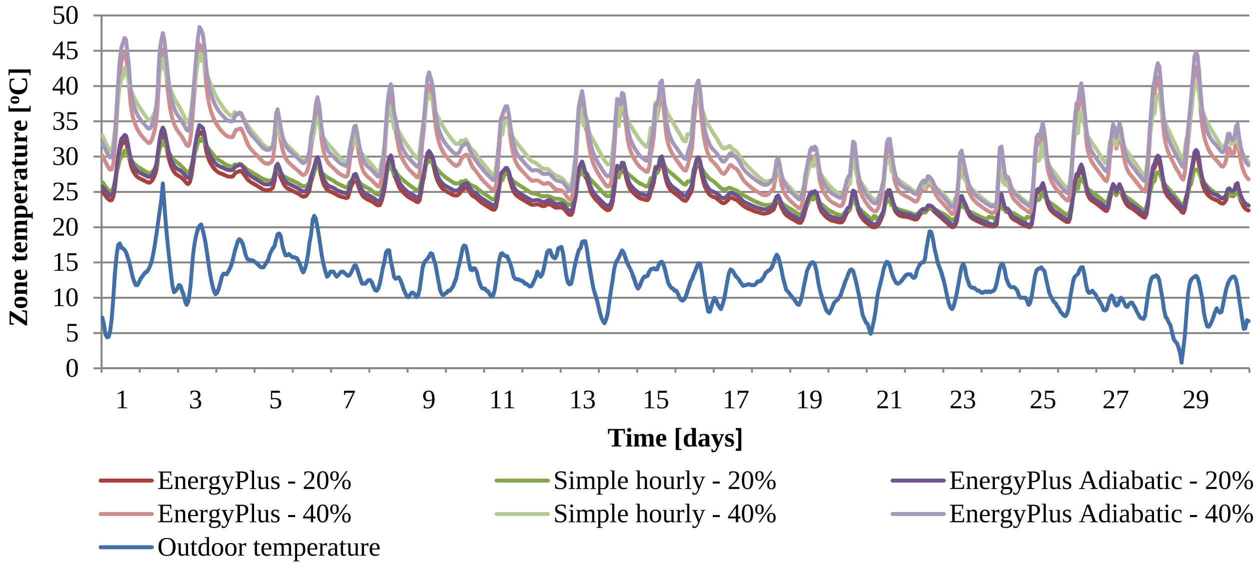

Figure 6: Comparison of temperature profiles for the month of September for a glazing-to-floor ratio of 20 and 40% and a standard insulation level for south orientation of Zone 1 obtained from the use of the simple hourly method in WinDesign and from dynamic simulations in EnergyPlus.

As can be seen, in cases when no active cooling is present, the temperature profile in Zone 1 for a standard-insulated house found from calculations based on the use of the simple hourly method is comparable with the temperature profile obtained from dynamic simulations using an adiabatic model and a coupled thermal zone model and this for both small and large glazing-to-floor ratios. However, in a well-insulated house, the temperature profile found from calculations based on the use of the simple hourly method shows better agreement with the temperature profile obtained from dynamic simulations using an adiabatic model, especially at large glazing-to-floor ratios. In the well-insulated house, the difference in temperature profiles obtained from the use of a coupled thermal model or an adiabatic model increases. For future use of the simple hourly method in design of well-insulated buildings, the implementation of a coupled thermal zone model might be considered. As a general difference in the well-insulated house, it can also be seen from *Figure* 7 that the temperature profile calculated by EnergyPlus rises and falls more quickly than the temperature profile calculated by use of the simple hourly method in WinDesign. Even though the temperature profiles show a similar trend, it becomes clear that the dynamics of the models are different. The main reason could be that the simple hourly method treats the thermal mass in a different way. This is especially the case in well-insulated buildings and might warrant from further research.

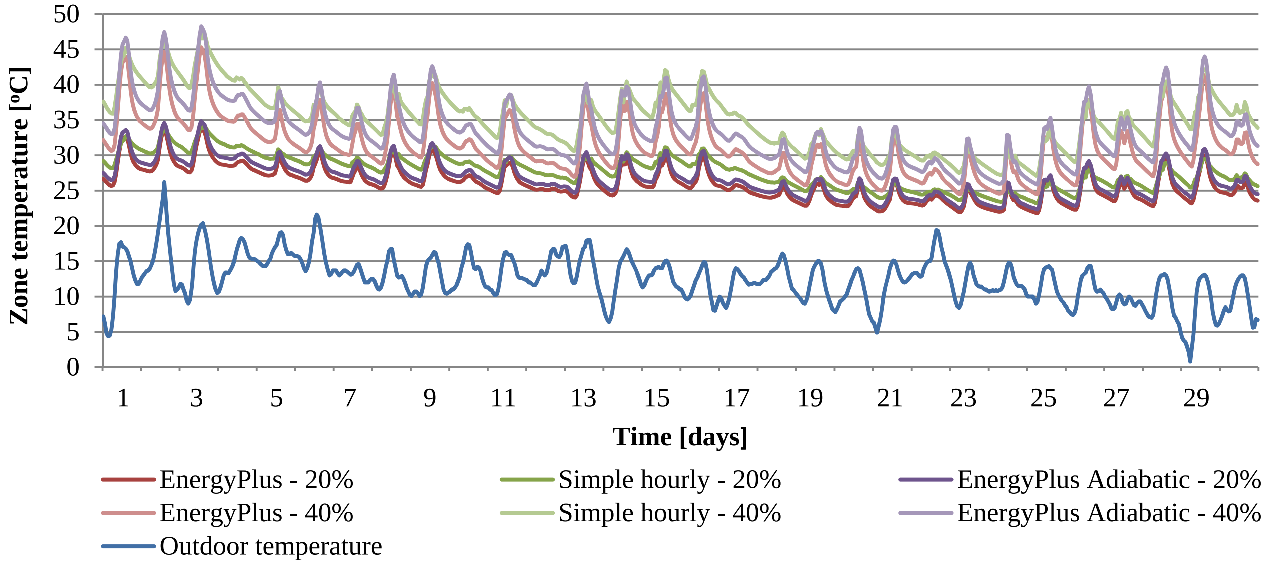

Figure 7: Comparison of temperature profiles for the month of September for a glazing-to-floor ratio of 20 and 40% and a high insulation level for south orientation of Zone 1 obtained from the use of the simple hourly method in WinDesign and from dynamic simulations in EnergyPlus.

4 Conclusion

Many simulation tools exist and can be used indirectly for the evaluation of the effect of different window designs, but few allow an easy comparison of the effect of window designs varying in orientation, configuration and size as they are often too difficult to learn or use in the early design phases, especially for the design of residential buildings. The tool described is developed as user-friendly calculation program based on simple input data and methods as defined in EN ISO 13790 to assist engineers and architects during the process of designing windows, but it can also be used more generally to predict building performance and carry out a quick parametric study. The tool makes it possible to compare and evaluate various window scenarios with different components, sizes, configurations and orientations, depending on the flexibility of each design case. The tool has several levels of evaluation, starting from the simple net energy gain of individual windows to the hourly calculation of energy consumption of a whole set of windows used in a dwelling and their effect on electricity consumption for artificial lighting, hours of overheating and economic performance. Because its input data are limited, the user could benefit from using the tool in the early phases of the design process, where the most important decisions are made. The workflow in the tool also supports this because each step in the tool increases in level of detail, which supports design decisions throughout the design process. At the beginning of the design process, for example, not all the building parameters are known. Often, the most important thing is to be able to see the orders of magnitude and be able to compare various solutions rather than make an exact calculation. Nevertheless, even though the tool is based on the implementation of simple methods in the European standard EN ISO 13790, it showed overall good agreement with results from detailed simulations in EnergyPlus. However, the application of the methods might benefit from further research if they are to be used for design of very well-insulated buildings.

Acknowledgements

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Paper IV

Full-service concept for energy efficient renovation of single-family houses.

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Full-service concept for energy efficient renovation of single-family houses

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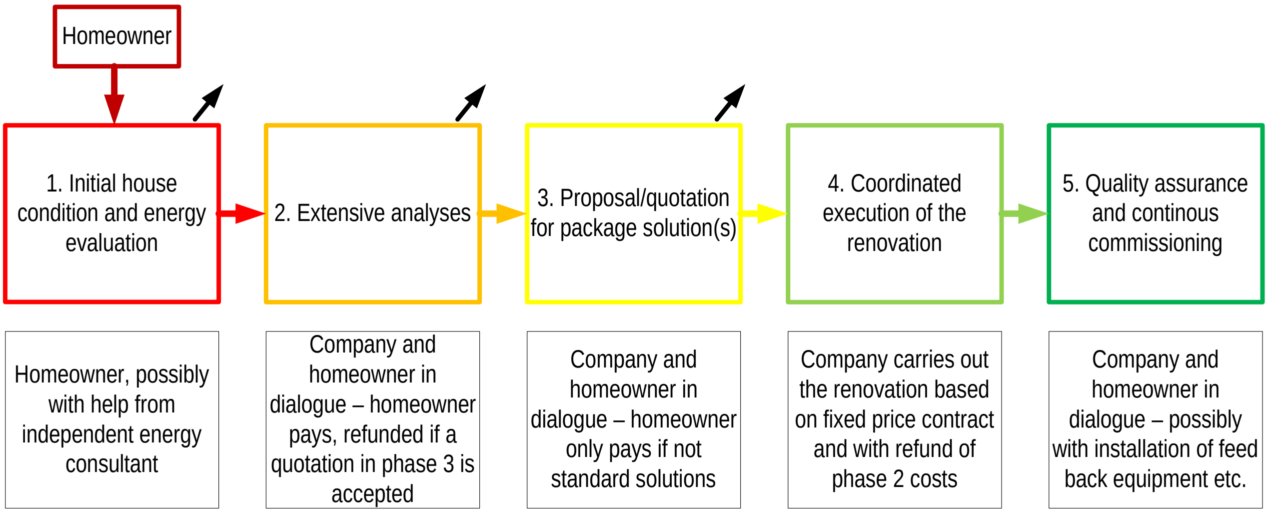
Extended abstract

There is a need for far-reaching energy efficiency improvements in connection with renovation if existing single-family houses in the Nordic countries are to have competitive power compared to new buildings on the future housing market. If the market is able to explain this to the homeowners there is an open market with undreamt-of possibilities. Good technical solutions exist but need to be combined based on the full range of (standard) solutions in order to reach the low primary energy level of new houses.

A one-stop-shop in the form of a full-service concept could be seen as a possibility to make it easy for the homeowner to realize far-reaching energy savings, provided that the building sector offers the solutions. Such one-stop-shops in the form of full-service providers of energy efficient renovation of single-family house are missing in the Nordic countries, although this service is vital to open up the market. The purpose of such shops, which may be a cheap internet shop, is to help homeowners with design and decision making process in connection with renovation of their house. The one-point-of-contact service provider may be a company/team of consultants and contractors. They can help to bring about a complete sustainable renovation solution including quotation for the work, financing and management of the contract work.

As part of the Nordic research project `SuccesFamilies´ with the purpose to change the business environment in order to speed up the implementation of sustainable renovation of single-family houses –a sustainable renovation concept suitable for different categories of single-family houses with regard to type and age has been proposed in this article. The sustainable renovation concept includes an ideal full-service concept and technical renovation solutions targeted to different types of single-family houses. The ideal full-service concept consists of 5 phases, going from initial evaluation of the house, to extensive analyses, proposal for package solutions, coordinated execution and operation and management of the house after renovation.



The idea is to inspire one-stop-shop providers of today and the future to improve their service. Based on analyses of existing full-service concepts the following improvements are suggested:

- Integrated analysis of the energy saving potential and physical conditions
- Extensive analyses such as thermography and blower door test to be able to come up with trustworthy fix price proposals with very limited reservations
- Focus on handling of the homeowners needs and wishes and making it easy to buy renovation services (like in a kitchen studio) and more focus on the non-energy benefits
- Offering of the full range of technical solutions and focus on reducing heating demand before introducing measures to ensure energy efficient energy supply
- Development of tools to quickly put together individual package solutions - based on configuration of standard solutions - and including visualization of the renovation project for the homeowner

Technical energy efficiency measures targeted to different types of single-family houses can be combined into concepts or packages of measures. If such packages should be attractive for the homeowner it is crucial to link energy efficiency measures to the normal renovation measures, in that way reducing the price of implementing the energy efficiency measures. Nordic single-family house owners can generally save about 75% on primary energy use and energy bill by installation of building envelope post-insulation, energy efficient windows, ventilation with heat recovery and an efficient energy supply system. This corresponds to the energy use level of a new house or better. Such renovation will amount to approximately EUR 100,000 and it may be difficult to obtain an economy in balance in the sense that the annual payment on a cheap loan (mortgage refinancing) to finance the renovation is not fully offset by the expected annual energy savings.

Therefore it is also important to address the non-energy benefits of energy efficient renovation, such as better and healthier indoor environment and comfort. Other benefits are improved lifespan of structures, increase in value of the house and less dependence on expected future higher energy prices. With due regard to these important benefits energy efficient renovation should still be attractive for the average homeowner. Better incentives structures, e.g. increased tax on energy and/or subsidy programmes might also speed up the implementation of a complete energy efficient renovation.

Full-service concept for energy efficient renovation of single-family houses

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Summary

There is a need for far-reaching energy efficiency improvements in connection with renovation if existing single-family houses in the Nordic countries are to have competitive power compared to new buildings on the future housing market. Good technical solutions exist but need to be combined based on the full range of (standard) solutions in order to reach the low primary energy level of new houses. A one-stop-shop in the form of a full-service concept could be seen as a possibility to make it easy for the homeowner to comply with possible future requirements to realize far-reaching energy savings in connection with extensive renovations, provided that the building sector offers the solutions. Such one-stop-shops in the form of full-service providers of energy efficient renovation of single-family house are missing in the Nordic countries, although this service is vital to open up the market.

As part of the Nordic research project `SuccesFamilies´ with the purpose to change the business environment in order to speed up the implementation of sustainable renovation of single-family houses –a sustainable renovation concept suitable for different categories of single-family houses with regard to type and age has been proposed in this article. The sustainable renovation concept includes an ideal full-service concept and technical renovation solutions targeted to different types of single-family houses.

Keywords: energy efficiency, renovation, single-family houses, one-stop-shop, full-service concept, technical solutions

1. Introduction

Detached single-family houses account for large share of the total number of dwellings in the Nordic countries. With a final energy use for space heating and hot water in the range of 135 to 200 kWh/m^2, existing single-family houses in the Nordic countries need to be significantly upgraded to be competitive compared to new buildings on the future housing market [1-4].

So far there has been limited attention to address the need for major renovation in existing detached single-family houses. The Nordic single-family house renovation market is dominated by a craftsman based approach with individual solutions, traditional warehouses ”do-it-yourself-shops” and some actors marketing single products [5]. In most cases the homeowner is therefore left to himself to compose the right “package” for renovation of his home. In order to ensure the homeowner a sustainable renovation to low primary energy level at a reasonable price, there is a need for a more integrated approach and application of the full range of technical solutions [6].

To speed up the implementation of sustainable renovation of single-family houses there is also a great need for full-service packages including consulting, contract work, follow-up, financing and operation and maintenance. There are few Nordic examples of such service models for renovation of single-family houses which entered the market recently. The success of these concepts is yet to be evaluated. However, most of these service models typically focus on application of only a few of the available technical solutions for renovation and have not been successful in realizing large scale energy efficiency gains [5].

A one-stop-shop in the form of a full-service concept could be seen as a possibility to make it easy for the homeowner to comply with possible future requirements to realize far-reaching energy savings in connection with extensive renovations, provided that the building sector offers the solutions. Homeowners need someone to take care of all relevant steps necessary for the renovation of the house including quotation for the work, financing and management of the contract work. Such one-stop-shops in the form of full-service providers of energy efficient renovation of single-family house are missing in the Nordic countries, although this service is vital to open up the market.

As part of the Nordic research project `SuccesFamilies´ with the purpose to change the business environment in order to speed up the implementation of sustainable renovation of single-family houses –a sustainable renovation concept suitable for different categories of single-family houses with regard to type and age has been proposed in this article. The sustainable renovation concept includes an ideal full-service concept in five phases, going from initial evaluation of the house, to extensive analyses, proposal for package solutions, coordinated execution and operation and finally management of the house after renovation and includes technical renovation solutions.

2. Full-service renovation concepts

A full-service or one-stop-shop renovation concept is defined as a documented series of actions that can be repeated and that produces individual renovated single-family houses aiming at fulfilling the defined requirements optimally. The term full-service renovation concept indicates that all relevant steps necessary for the renovation of the house are included [5]. Typically, the requirements are defined by the homeowner and building code, e.g. requirements to heat loss (U-values), energy performance (energy consumption), indoor environment (indoor air quality, thermal comfort and daylight) and architectural quality. As mentioned previous, a full-service or one-stop-shop renovation concept could be seen as a possibility to make it easy for the homeowner to comply with the requirements. The one-stop-shop can help the homeowner with design and decision making process in connection with renovation of the house.

Analysis of existing full-service renovation concepts has shown that they can generally be improved by:

- A more integrated analysis of the energy saving potential, physical conditions and technical solutions using the full range of solutions, i.e. advice to reduce heating demand before introducing measures to ensure energy efficient energy supply.
- Including advanced analyses such as thermography, possibly complemented by U-value measurements [7], a and blower door test that the homeowner can buy and may get refunded if they buy a renovation solution – which enables the company offering full-service renovation to come up with trustworthy fixed price proposals with very limited reservations.
- Better handling of the homeowners needs and wishes.
- Package solutions made up from different standard parts, making it easy to carry out sustainable renovation (like e.g. in a kitchen studio)
- Making the energy efficiency improvements more attractive and cost effective by focusing on the non-energy benefits.
- Developing tools to quickly put together proposals for full-service renovation including drawings and calculations that can visualize the renovation project for the homeowner.

2.1 Full-service renovation – ideal concept

An ideal one-stop-shop concept for preparation and execution of complete package solutions for sustainable renovation of single-family house is suggested. The idea is to inspire one-stop-shop providers of today and the future to improve their service. The concept consists of five phases, going from initial evaluation of the house to extensive analysis, proposal for package solutions for sustainable renovation, detailed planning and execution; and operation and management of the house after renovation, see Fig. 1.

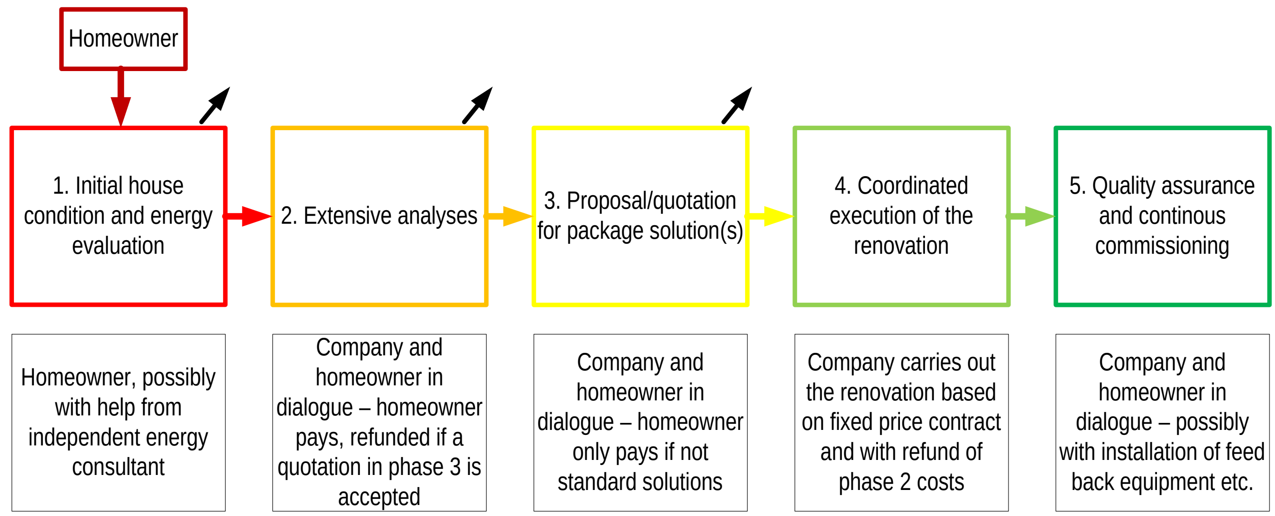

Fig.1. Full-service or one-stop-shop concept.

The different phases in the concept are briefly described below.

2.1.1 Initial house condition and energy evaluation (phase 1)

This initial analysis of house condition and energy saving potential should be free of charge and may be carried out by the homeowner using an internet tool / simple model, provided by the one-stop-shop/company offering complete renovation package solutions. Alternatively, the homeowner could ask for help from an independent energy consultant. A basis for the analysis is a possible existing energy label, house condition report, drawings, pictures and other relevant documents.

Information about house type, year of construction, existing building envelope structures (U-values), existing heating and ventilation system and areas is needed. Furthermore, since user behaviour influences energy use, information about indoor environment, i.e. indoor temperature, air change rate, venting habits etc., is required. Based on this information, the analysis provides the homeowner with a guided choice of energy efficiency measures and a rough estimation of possible savings and other measures based on his needs and wishes for improvements of the energy performance and living comfort etc. Furthermore, indoor environment benefits, renovation costs, financing expenses, increase in value of the house etc. are documented. The homeowner also receives documentation/visualisation of the effect of energy and non-energy benefits on the cost of financing the renovation. Besides this, the company provides the homeowner with information about relevant legislation and subsidy possibilities.

2.1.2 Extensive analyses (phase 2)

The initial analysis is followed by more extensive analyses. This service is carried out by the company in dialogue with the homeowner and paid for by the homeowner but refunded if a renovation package solution is bought in phase 3. The extensive analyses also have as purpose to provide the company with knowledge that allows for a safe foundation for providing the homeowner with an economical attractive and fixed price quotation for the renovation work. The extensive analyses could include relevant services such as blower door testing of the building envelope´s air tightness, building thermography to reveal thermal bridges and possibly heat loss measurements and estimation of remaining life time of building components.

As an output from phase 2 the company gathers an initial house evaluation report with the results of the analyses that can be used for the homeowner’s consideration of future renovation work. The evaluation report includes a clarification of the needed renovation work, needs and wishes for improvement, order of priority and estimated costs. Furthermore, advice on how to improve the energy performance of the house in connection with needed renovation work is stated in the report. Besides this, the evaluation report should include an estimation on the economic implications of normal step-wise renovation, thorough sustainable renovation and demolition of existing house and building of a new house (if relevant). In some cases, a major sustainable renovation is not relevant and therefore the company should offer to make a detailed long term plan for renovation and modernization, which optimizes the economy in relation to the house owner’s wishes and needs.

2.1.3 Proposal for package solutions (phase 3)

In this phase proposals for renovation package solutions are put together, including quotation for the work, financing and management of the contract work. The main point is that the typical homeowner needs help in the design and decision making process. As a starting point for this phase, the company organises a meeting with the homeowner to discuss the initial house evaluation report, needs and wishes, technical solutions and available budget. Output from this meeting is used for further analyses of possible technical renovation measures in order to result in trustworthy proposals for sustainable renovation including energy and non-energy benefits, economic profitability, financing, plan for renovation, durability issues and fulfilment of user needs and wishes. Economic profitability and priority of measures can be analysed using e.g. the criterion of cost of conserved energy incl. twofold benefit of energy savings and rehabilitation of the building components physical condition.

The company should be able to carry out this phase within a maximum of 4 hours provided that the right system for configuration of technical standard solutions is in place including simplified but accurate calculation models. If the homeowner wants special solutions that are not standard it may not be free of charge getting quotation for renovation work.

As output from phase 3 the homeowner receives a pre-project folder with fixed priced proposal(s) for optimized package solutions for renovation including visualization/documentation of the effect on energy use and energy bill, household economy (short and long term, including effect of increased value of the house), indoor environment and other durability and maintenance issues.

2.1.4 Coordinated execution of the renovation work (phase 4)

This phase is carried out based on the homeowner's evaluation of the pre-project proposals for sustainable renovation. If the homeowner chooses to accept any of the proposals, any remaining economic and financing issues are clarified and a contract for renovation work is signed. The contract could include approval of a possible loan and/or governmental subsidy or contract details could be fine-tuned considering the specific situation, e.g. some extra work or/and better products might be included. Signing of the contract could be based on a fixed priced contract work carried out on risk of the facilitator of the full-service package solution or it could be based on energy performance contracting (EPC) utilized and redeveloped to match the single-family house renovation market.

After signing of the contract, drawings and a detailed work description are prepared and the contract work is carried out, managed and quality assured by the company and the affiliated professional group of consultants and contractors. However, as the traditional market for renovation is very much a do-it-yourself-culture, service packages should be flexible to handle a customer wish for contributing to the process of carrying out the work.

2.1.5 Quality assurance and continuous commissioning (phase 5)

After the execution of the sustainable renovation an important phase begins. Quality of the renovation work is inspected, e.g. by a independent certified energy consultant, and heating and ventilation systems are commissioned according to the project, and this not only once but on a continuous basis. Continuous or Life-Cycle Commissioning (LcCx) in connection of existing buildings is usually considered as "a systematic process for assuring that buildings operate, function and are maintained optimally according to owner expectations and user needs." [8]

After visit of the independent energy consultant the homeowner is provided with a follow-up evaluation report. Besides this, the homeowner also receives a user manual including a plan for continuous commissioning of the house (like car service) to make sure that the house functions optimally according to owner expectations and user needs and the peak energy performance is continuously reached. Since user behaviour can have large impact on energy use, it is important to present the homeowner with information on the consequences for energy use and indoor environment if the house is not operated as prescribed.

To check if expected energy savings are fulfilled equipment for measurements and presentation of weather data, energy use, and actual use of the house, e.g. ventilation, indoor temperature and opening of windows is needed. When relevant such system may suggest actions to reduce energy use, e.g. indoor temperature, ventilation rate or hot water use, based on comparison with the assumptions made in the calculation of expected energy use and savings in phase 3 – including estimate of the consequences of the more energy friendly use of the house. A validated model of the house could be the basis for intelligent control of active and passive systems for heating, cooling, ventilation, solar shading etc., based on measurement of actual and forecasted weather data and use of the house. The Danish Energy Saving Trust is offering a new program to homeowners (My E-Home, [9]) that could – with the right equipment - be used for online control of energy use in single-family houses, i.e. to switch on, turn off or adjust the heating and ventilation system etc.

2.2 Full-service concepts for different single-family houses

Nordic single-family houses vary in age, size, architecture, insulation standards etc. Hence, a standard renovation concept might not be applicable to all types of houses. Each renovation project with different framework conditions may need to be evaluated separately. Accordingly, it may be relevant to focus full-service concepts to a certain category of single-family houses.

Analysis of the building stock in the Nordic countries as part of the `SuccesFamilies´ project showed that the typical single-family houses identified to have large primary energy saving potential almost descend from the same time period in each Nordic country. The first segment is houses built in large numbers during the 1960´s and 1970´s before tightening of the insulation standards in the building codes in the late 1970's due to the oil crisis. The second segment is houses built before 1945 (except for Finland) where a large part of them has been renovated, but energy renovation of those houses today would still account for a large energy saving. The third segment is type houses from the post-war period in Finland, houses that are all individual but built in the same way with the same materials. In Fig. 2, an illustration of some of the type houses can be seen.

Fig. 2 Typical single-family houses in the Nordic countries. From left to right: Danish house built before 1945, Norwegian house built before 1945, Post-war Finish house, Danish house built in 1960/70´s.

The renovation process for these different categories of single-family houses may be very similar but the technical solutions are different. For example, many people regard facades of typical Danish single-family houses built before 1945 (so-called master builder houses) as being worth preserving. Facades can be thermally improved by filling the cavity with e.g. granulated mineral wool and by installing new storm windows with energy efficient glazing whereas a facade constructed from wooden framed walls, as can be found in Norwegian single-family houses built before 1945, may be more likely to be renovated along with adding external insulation.

Hence, technical renovation concepts can be defined for these different categories of single-family houses.

3. Technical renovation concepts

A technical renovation concept is defined as a package of solutions targeted to a certain category of house (type and age) [5]. The package of technical solutions carried out during an overall or step wise planned renovation should be a good combination of the full range of technical solutions, especially in order to reach a low primary energy level.

3.1 Technical renovation solutions

To reach a low primary energy level, different technical solutions such as renovation of roof, facade, changing windows, installation of energy efficient heating systems, and establishing a ventilation system etc., need to be combined. The technical principles are illustrated in Fig. 3 in recommended order of application and an indication of the needed level of energy efficiency of these principles is also included. Focus is on technical solutions relevant for renovation of typical single-family houses in the Nordic countries.

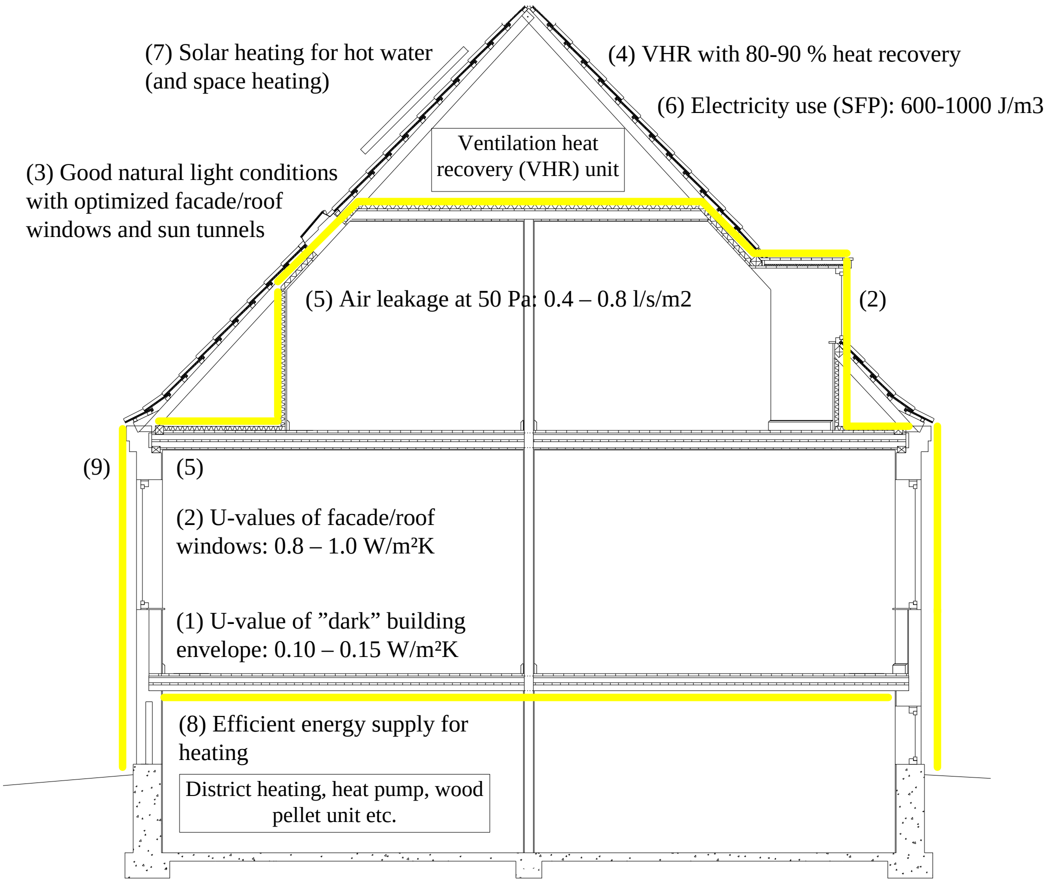

Fig. 3 Technical renovation principles in order of application. (1) Reduced transmission heat losses from opaque building envelope (2) Reduced transmission heat losses, good solar gains and light transmission from the transparent building envelope (3) Optimized utilization of passive solar heat gains (4) Minimized ventilation heat losses (5) Minimized infiltration heat losses (6) Minimized ventilation electricity use (7) Minimized water heating demand (8) Efficient energy supply for heating (9) Mainly passive measures for overheating control.

Besides the technical principles illustrated in Fig. 3, also intelligent control and continuous commissioning and the installation of energy efficient electrical appliances need to be considered.

3.2 Packages of technical renovation solutions

Technical renovation solutions/measures can be combined into technical renovation concepts or packages. Such packages have been defined and analysed as part of the SuccesFamilies project, see Table 1. Package #1“Existing house” is to be regarded as the scenario where renovation may be carried out in the form of e.g. a new roof and/or new exterior wall rainscreen, but no measures to improve energy efficiency are implemented.

Table 1 Packages of technical renovation solutions.

#	Package	Energy efficiency measures	Technical principles
1	Existing house	No energy efficiency measures	Traditional renovation
2	”Easy-to-carry-out” measures	Insulation and sealing of building envelope, windows that allow for utilization of passive solar heat gains and daylight without excess overheating.	Minimized transmission and infiltration heat losses, utilization of passive solar heat gains and daylight etc
3	+Efficient energy supply system	Heat pump, district heating, low temperature system, energy efficient circulation pumps, insulation of heating pipes etc.	Efficient energy supply for heating
4	+ Ambitious measures	Mechanical ventilation system with heat recovery (VHR), solar energy for hot water etc.	Minimized ventilation heat losses and water heating demand
5	+ Extensive measures	Façade insulation that changes the appearance of the house, or measures that are far reaching but allow for a large reduction in the primary energy use	Various

A complete energy efficient renovation of a typical house includes post-insulation and sealing of the buildings envelope - roof/ceiling, façade, windows/doors and foundation and maybe slab on ground - installation of a mechanical ventilation system with high efficiency heat recovery and low electricity use and if not already there, an energy efficient heating system based on district heating, heat pump etc. This package of technical solutions can be carried out during an overall or step wise planned renovation dependent on the condition of the house, the financial possibilities of the homeowner etc.

3.3 Example – Packages of solutions for Danish single-family houses built during the 1960/70´s

An example of calculation of packages of technical solutions for energy efficient renovation is given below.

Calculation have been based on analysis of a typical Danish single-family house built in 1972 with a heated floor area of 155 m^2 and heated by a gas-fired boiler.

The house is one of the many 450.000 Danish typical single-family houses built during the 1960/70´s. External walls of these houses are constructed as cavity or framed walls with an insulation thickness of 75-100mm, an outer leaf of 110mm masonry and an inner leaf of 100mm of light-weight concrete or 110mm of masonry. Windows are typically wooden (coupled) windows which need a replacement.

Primary energy use and savings for individual technical renovation measures are stated in Table 2. The installation of a heat pump has not been considered as in future, most Danish single-family are expected to be connected to the district heating network.

Table 2 Primary energy use and savings (kWh/m^2 per year) for typical individual technical renovation measures.

#	Technical renovation measure	Primary energy	Energy savings
	Existing house from 1972, 155 m^2, gas boiler	246	-
A	External wall insulation, 100-150mm (U = 0.19 W/m2K)	225	20
B	345 mm insulation in roof (U = 0.10 W/m2K)	230	16
C	External wall insulation, 200-250 mm (U = 0.13 W/m2K)	222	24
D	150 mm extra insulation in floor (U = 0.15 W/m2K)	232	14
E	New energy efficient windows (U = 1.34 W/m^{2}K)	200	46
F	New low-energy windows (U = 0.80 W/m^{2}K)	196	49
G	VHR, efficiency: 80%, SFP: 1 kJ/m3, infiltration: 0.13 h^{-1}	231	15
H	VHR, efficiency: 85%, SFP: 0.6 kJ/m3, infiltration: 0.13 h^{-1}	218	27
I	Replacement of existing circulation pump (60W) with smaller energy efficient pump (25W)	240	5
J	Replacement of existing boiler with new condensing boiler	214	32
K	Solar panels for domestic hot water	241	5

3.3.1 Package of solutions

Based on the individual technical renovation measures, the influence of different packages of technical renovation solutions, composed according to the principle in Table 1, has been investigated. In Table 3, the space heating need, primary energy use and savings and overheating hours for each package of solutions are stated.

Table 3 Energy use and savings (kWh/m^2 per year) and thermal indoor climate for package of solutions.

		Energy use			**Overheating hours, class II >26°C**		
#	Package of solutions	Space heating	Primary energy	Primary energy savings	Venting 1.5 h^{-1} (Ref)	Venting 3.0 h^{-1}	External shading
1	Existing house	160	246	-	217	110	58
2	A+B+E	81	154	38%	397	155	104
3	A+B+E+H+I+J	55	104	58%	363	148	90
4	A+B+E+H+I+J +K	55	100	59%	363	148	90
5	B+C+D+F+ H+I+J +K	35	66	73%	270	93	68

Table 3 shows that in order to reach a low primary energy level comparable to new Danish buildings today [10], a complete energy efficient renovation with installation of building envelope post-insulation, energy efficient windows, ventilation with heat recovery and an efficient energy supply system is needed. A side effect of insulation measures may be some overheating, which can effectively be avoided by external movable solar shadings and/or to some extent by higher venting rate by use of e.g. automatically controlled windows. A ventilation system with heat recovery will also contribute to a good thermal comfort by draught-free supply of fresh air and make sure of an excellent air quality.

In general, calculation of packages of energy efficient renovation solutions targeting the three segments of houses showed that primary energy use and heating bill could be reduced with up to about 75% or a factor 4 corresponding to the level of a new house or better. The potential is particularly high for houses with electric heating where installation of a heat pump and water-based heat supply system will reduce primary energy use and heating cost with about 70%. Besides efficient energy supply systems, VHR systems are important in order to reach a low primary energy level and a good indoor environment after renovation of single-family houses. VHR systems can give substantial final energy reduction, but the primary energy benefit depends strongly on the type of heat supply system, the amount of electricity used for VHR and the air tightness of the house. It is important to consider the interaction between heat supply system and VHR systems to reduce primary energy use [11].

The investment needed to reach a low primary energy level and a good indoor environment after renovation has been calculated to be in the range of EUR 100,000. With this investment cost, it is generally difficult to obtain an economy in balance in the sense that the annual payment on a cheap loan, e.g. mortgage refinancing, to finance the investment is not fully offset by the expected annual energy savings. In other words, if packages of technical energy efficiency measures should be attractive for the homeowner it is crucial to link energy efficiency measures to the normal renovation measures, in that way reducing the price of implementing the energy efficiency measures. Furthermore, it is also important to address the non -energy benefits of energy efficient renovation, such as better and healthier indoor environment and comfort. Other benefits are improved lifespan of structures, increase in value of the house and less dependence on expected future higher energy prices.

4. Conclusion

There is a need for far-reaching energy efficiency improvements in connection with renovation if existing single-family houses in the Nordic countries are to have competitive power compared to new buildings on the future housing market. If the market is able to explain this to the homeowners there is an open market with undreamt-of possibilities. Good technical solutions exist but need to be combined based on the full range of (standard) solutions in order to reach the low primary energy level of new houses. A one-stop-shop in the form of a full-service concept could be seen as a possibility to make it easy for the homeowner to realize far-reaching energy savings, provided that the building sector offers the solutions. Such one-stop-shops in the form of full-service providers of energy efficient renovation of single-family house are missing in the Nordic countries, although this service is vital to open up the market. The purpose of such shops, which may be a cheap internet shop, is to help homeowners with design and decision making process in connection with renovation of their house. The one-point-of-contact service provider may be a company/team of consultants and contractors. They can help to bring about a complete renovation solution including quotation for the work, financing and management of the contract work.

An ideal full-service concept in five phases has been proposed, going from initial evaluation of the house, to extensive analyses, proposal for package solutions, coordinated execution and operation and finally management of the house after renovation and different package solutions of technical energy efficiency measures targeted to different types of single-family houses have been investigated. Analyses show that typical single-family houses can be renovated to the level of energy performance required for new houses today or in some cases renovated to low-energy level. Nordic single-family house owners can generally save about 75% on primary energy use and energy bill by installation of building envelope post-insulation, energy efficient windows, ventilation with heat recovery and an efficient energy supply system. The finances of such a complete energy efficient renovation are, however, not fully offset by the expected annual energy savings. But with due regard to all the non-energy benefits, such as better and healthier indoor environment and comfort, increase in value of the house and less dependence on expected future higher energy prices, a complete energy efficient renovation could still be attractive for the average homeowner. Better incentives structures, e.g. increased tax on energy, low interest loans and/or subsidy programmes might also speed up the implementation of a complete energy efficient renovation.

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